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SONIC BOOM LITERATURE SURVEY. VOLUME II. CAPSULE SUMMARIES

Larry J. Runyan, et al

Boeing Commercial Airplane Company

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16. Abstract

The purpose of this document is to provide a reference for investigators in the field of sonic boom to help in eliminating possible duplication of future efforts by compiling in one document the results of all published sonic boom investigations.

Volume I contains a summary of the current state of the art. Its purpose is to acquaint the reader with the subject in sufficient depth to allow evaluation of subsequent technical work or the completion of current unfinished investigations. Fundamental concepts, ideas, and study results of sonic boom work in the areas of generation, propagation, minimization, human response and social criteria, structural response, animal response, threshold Mach number, simulation methods, and instrumentation techniques are summarized. Aspects of sonic boom that need further research are also identified.

Volume II consists of a comprehensive annotated reference of all sonic boom studies in the form of capsule summaries. Each capsule summary contains a complete reference of the paper, a statement of its purpose, a summary of significant results, a comparison of the work with other similar papers, and an evaluation of the paper. Subject and author indexes are given at the end of the report.

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PREFACE

The authors gratefully acknowledge the assistance of Mr. George T. Haglund for numerous suggestions and comments, Mr. J. P. Taylor for his help in obtaining numerous reports, Ms. Grace Pierce in obtaining all of the papers necessary to compile this document, and Mr. B. Dillner, Program Manager. The authors also acknowledge the assistance and contributions made by Mr. Thomas H. Higgins, Technical Monitor and Mr. J. Kenneth Power, Chief-Aircraft Noise and Pollution Branch.

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1.0 INTRODUCTION

There has been a considerable amount of work done over the last 25 years dealing with the subject of sonic boom. The purpose of this report is to help preserve this work and avoid duplication of future studies by compiling in one document individual annotated capsule summaries of all published sonic boom investigations. Each capsule summary contains a complete reference for the paper, a statement of the purpose of the work, a summary of significant findings, a comparison of the paper with other similar papers, and an evaluation of the paper. The capsule summaries have been grouped into thirteen separate subject areas and are ordered chronologically (except for several papers at the end of each section) within each subject area. Each capsule summary contained in this volume is numbered with the subject abbreviation and a sequential number. For example, capsule summary AR-12 would be the twelfth consecutive paper in the Animal Response section.

The following bibliographic sources were consulted in compiling the list of papers to be included in this document:

1. BIBLIOGRAPHY ON SONIC BANGS

   Jill Wadsworth
   Royal Aircraft Establishment; Library Bibliography
   No. 287, January 1968

   This source lists 478 references involving all aspects of generation, propagation, and response to sonic booms. Sources consulted in making this bibliography were R.A.E. Library subject catalogue, NASA STAR 1962-67, International Aerospace Abstracts 1962-67, Engineering Index 1955-67, British Technology Index 1962-67, Ministry of Aviation R and D Abstracts 1963-67, F.A.A. "Sonic Boom Bibliography," October 1966. T.D.C.K. (Netherlands) "Sonic Boom Literature Survey," May 1966 (T.D.C.K. 45316), Ministry of Aviation TOL "Noise Bibliography" to 1967 and R.A.E. Library S.S.T. list 1967.

2. THE EFFECTS OF SONIC BOOM, A HANDBOOK FOR THE CIVIL ENGINEER

John H. Wiggins, Jr.
Prepared for the Air Force Institute of Technology
Wright-Patterson Air Force Base, Spring 1969.

This notebook contains a chronological bibliography of sonic boom work which lists 446 references from 1946-1968.

3. SUBJECT CARDS AND AUTHOR CARDS FOR PUBLICATIONS RETAINED IN THE FILES

National Academy of Sciences, National Research Council, Washington, D. C., 1971.

This source contains approximately 300 sonic boom references for the period 1959-1971.

4. AN ANNOTATED BIBLIOGRAPHY ON ANIMAL RESPONSE TO SONIC BOOMS AND OTHER LOUD SOUNDS

A report of the Subcommittee on Animal Response Committee on SST-Sonic Boom.
National Academy of Sciences, National Research Council, Washington, D. C., 1970.

Approximately 40 references from the 1959-1970 period concerning the effect of sonic booms and other impulsive sounds on animals are listed in this bibliography.

5. BIBLIOGRAPHY GENERAL, FPS NOISE STUDY LAW

Zimmerman and Ware
As of August 11, 1971.

This bibliography contains 95 references concerning laws governing noise and sonic booms.

. TRANSPORTATION NOISE BULLETIN

Transportation Noise Research Information Service
Highway Research Board, Division of Engineering, National Research Council, National Academy of Sciences, National Academy of Engineering, Volume 1, Number 1, October 1971.

This bibliography contains over 200 references on sonic boom studies for the 1969-1971 time period.

7. NASA STAR and INTERNATIONAL AEROSPACE ABSTRACTS

These sources were used to obtain references in the 1971-1973 time period.

. The bibliographies of various NASA Technical Notes and other papers were also scanned to assure that the list of references was complete.

. total of approximately 650 papers, which were drawn from the above ref- .ists, are sumarized in this document.

2.0 GENERATION

G-1
LINEARIZED SUPERSONIC FLOW
Wallace D. Hayes
Ph.D. Thesis, Cal. Inst. of Tech., 1947
AMS Report No. 852, Reprinted October 1968

This thesis deals with the study and development of linearized supersonic theory, and with the application of the theory to various examples. The main contribution to sonic boom theory is the "supersonic area rule." This is the rule which allows an arbitrary 3-D shape to be represented by an equivalent body of revolution.

The "supersonic area rule" is a result of the following physical concepts. Consider a non-axisymmetric body aligned parallel to the Z-axis in a cylindrical coordinate system, where in this case Z is a time variable.

An observer at a given value of r and θ will be affected by all points in the upstream Mach cone from that point. The upstream Mach cones represent surfaces of coincident signals; disturbances from all points of a cone arrive simultaneously at the point of the observer. When the observer is a large distance from the body, the surface of the cone in the vicinity of the body can be approximated by a plane. Since disturbances from all points of the plane arrive simultaneously, it is impossible for the observer to distinguish between the influence of different points of the plane. For this reason, these disturbances can all be concentrated at the intersection of the plane with the body axis and still exert the same effect on the observer. A system of parallel cutting planes can, therefore, be used to find a linear distribution of sources and sinks which represents the body. These sources and sinks, in turn, define an equivalent body of revolution. An observer at a different value of θ will, in general, see a different equivalent body of revolution due to the fact that the cutting planes will intersect the non-axisymmetric body from a different angle. For a good illustration of the ideas of this paragraph see capsule summary G-5.

Hayes' purpose in deriving this rule was that it allowed the wave drag of an arbitrary body to be determined by computing the wave drag of the equivalent linear distribution of singularities. The utility of this rule in sonic boom calculations lies in the fact that it enables one to use Whitham's theory (see capsule summary G-3), which, in general, applies only to bodies of revolution, to find the flow field characteristics around any body shape.

The rest of the thesis gives a complete treatment of linearized supersonic flow beginning with the fundamental theory and then dealing with the topics of planar systems, wing theory, wave and vortex drag, and flow about bodies of revolution.

Lomax (capsule summary G-5) and Walkden (capsule summary G-6) later make good use of the area rule. Lomax uses it to find the wave drag of an arbitrary lifting or non-lifting body, and Walkden uses it to find the shock pattern of a wing-body combination.

This thesis, along with Whitham's paper, "The Flow Pattern of a Supersonic Projectile," provides the complete basis for the theory needed to calculate the sonic boom due to volume of any body in a uniform supersonic flow-field.

G-2
LINEARIZED COMPRESSIBLE-FLOW THEORY FOR SONIC FLIGHT SPEEDS
Max A. Heaslet, Harvard Lomax, and John R. Spreiter
NACA Rep. 956, 1950

This report investigates the range of applicability of linearized theory for Mach numbers near one. Its relationship to sonic boom theory lies mainly in the treatment given to the "area rule."

The "area rule" is referred to by the authors as the "concept of equivalent source position." (For a brief explanation of the area rule see capsule summary G-1). The "area rule" is used for the same purpose here as it was by Hayes--to compute the wave drag of an arbitrary body. The method is slightly different than that of Hayes, and the unique treatment of the "area rule" is very helpful in understanding this basic concept.

The rest of the paper deals mainly with solutions to the linearized potential equation for a variety of transonic flows.

G-3
THE FLOW PATTERN OF A SUPERSONIC PRO[illegible]
G. B. Whitham
Communications on Pure and Appl. [illegible] cs
Vol. V, 1952, 301-348

In this paper Whitham deriv[illegible] calculating the first approximat[illegible]tire flow field surrounding any [illegible]tion in supersonic flight. The assum[illegible]ying this theory are that the body is [illegible], pointed at the nose with the front sh[illegible]ached. However, even if these conditions are not satisfied, it may still be used to deduce the behavior of the flow at large distances.

Whitham's theory is based upon the following hypothesis: linear theory gives a valid first approximation <u>everywhere</u> in the flow field provided that the characteristics are corrected to account for cumulative non-linear effects. The reason for making this hypothesis can be found from an examination of the underlying physical ideas. In linear theory it is assumed that disturbances are propagated at a constant speed equal to the speed of sound in the main stream; the effect of velocity perturbations on the local speed of sound and the convection of sound with the moving fluid is not taken into account. When such an approximation is made in calculating the propagation of disturbances over small distances the error made is small. However, the error accumulates with distance. To get a complete picture of the flow-field it is necessary to use the local speed of propagation, which is equal to the local speed of sound plus the local fluid velocity. Thus linear theory gives the correct variation of physical quantities along the characteristics, but predicts the wrong shape for the characteristics. Instead of the straight-line characteristics of linear theory, given by $x - \alpha r$ = const, the characteristics of Whitham's theory are curved as a result of the cumulative nonlinear effects. These corrected characteristics are given by

$y(x,r)$ = const. (Here x is the distance along the axis from the nose of the body, r is the radial distance from the body, and $\alpha = \sqrt{M^2-1}$.) It is important to note that Whitham corrects only the x (and not the r) location of the characteristics.

To determine the expression for y, the condition that the slope of the characteristics be given by $dx/dr = \cot(\mu+\theta)$ is used, where μ is the local Mach angle and θ is the local flow direction. The quantities μ and θ are functions of the local perturbation velocities, u and v, which in turn are functions of the distance from the body and the characteristics of the body.

A function $F(y)$ is defined which arises naturally when relating the body characteristics to the flow quantities. This function is fundamental to the theory and for "smooth" bodies (bodies having no slope discontinuities) is given by:

$$F(y) = \frac{1}{2\pi}\int_0^y \frac{s''(t)\,dt}{\sqrt{y-t}}$$

where t is a dummy variable and $s(x)$ is the cross-sectional area of the body. A more complicated Stieltjis integral is derived for bodies having discontinuities in slope.

The corrected characteristics are determined from the F-function by the following equation, which is valid for large $\alpha r/y$:

$$y = x - \alpha r + kF(y)r^{1/2} \text{ where } k = \frac{\gamma+1}{\sqrt{2}}M^4\alpha^{-3/2}$$

The condition that $\alpha r/y$ be large means that the ratio of the distance from the body axis to the distance from the nose at which the specified characteristic intersects the body must be large. This is strictly satisfied only on shocks and at large distances from the body. However, as Lighthill points out (see capsule summary G-4), this equation is a good approximation at all points in the flow field.

In regions where the characteristics intersect to form a limit line the values given for the physical quantities cease to be unique. This breakdown is remedied by the insertion of shocks which cut off the continuous solu... fore this occurs: the characteristics meet the shock before they meet each other. The orientation of the shocks is determined from the characteristics by the following geometrical property (known as the "angle" property), which is a consequence of the Rankine-Hugoniot relations: if two regions of supersonic flow are separated by a shock, then to first order in the strength, the direction of the shock bisects the Mach directions of the two regions of the flow. Hence the shock is inserted at the intersection of the characteristics so that it bisects the angle of intersection. Based on this property, Whitham derives a geometrical method, known as the "area-balancing" technique, for locating the shocks and following their progress to infinity (in a homogeneous atmosphere). Basically, this technique consists of passing lines through inflection points of the $F(y)$ curve at which the slope is positive such that the lobes cut off on each side of the curve are equal in area. The slope of the line is determined by the radial distance at which the location of the shock is desired. This slope, together with the points at which it intersects the F-curve can be used to determine the strength of the shock at a given location using equations derived by Whitham.

The expression for the shock strength is derived using the Rankine-Hugoniot relations. The asymptotic expression at large distances from the body for the bow shock overpressure is:

$$\frac{\Delta P}{P_o} = \frac{2^{1/4}\,\gamma(M^2-1)^{1/8}}{(\gamma+1)^{1/2}\,r^{3/4}}\left\{\int_0^{y_o} F(y)dy\right\}^{1/2} \quad \text{Whitham's Asymptotic Formula}$$

where P_o is the undisturbed pressure and y_o is the value of y which maximizes the integral. This is one of the most important and well-known equations in sonic boom theory. It shows that in the "far-field," which is the region on the bow shock for which $y \approx y_o$, the bow shock overpressure is inversely proportional to the three-fourths power of the distance from the body.

Additional formulas derived by Whitham show that, in the far-field, the pressure signature takes the shape of an "N-wave." In this signature there is an initial pressure rise given by the above equation. The overpressure then decreases linearly to minus this value at the rear shock, where it jumps almost to zero and then decays asymptotically to zero.

In the "near-field" (in this region the effect of the body shape on the boom intensity is a variable dependent upon the distance from the body, while in the far-field the effect of the body shape does not vary with distance) the asymptotic formula cannot be used. For this region Whitham gives two equations which are used extensively in later investigations. These are:

$$\frac{\Delta P}{P_o} = \frac{2^{1/4}\,\gamma(M^2-1)^{1/8}}{(\gamma+1)^{1/2}\,r^{3/4}}\left\{\int_0^{y} F(y)\,dy\right\}^{1/2} \quad \text{Whitham's Non-asymptotic Formula}$$

$$\frac{P(y)}{P_o} = \frac{\gamma M^2\,F(y)}{\sqrt{2}\,(M^2-1)^{1/8}\,r^{1/2}} \quad \text{Whitham's General Formula}$$

Here the first equation is the same as Whitham's asymptotic formula except that the upper limit of integration is y instead of y_o. This means that the integration is carried only to the point at which the characteristic which meets the shock at the radius of interest intersects the body. This equation again gives only the bow shock overpressure and can be used only for bodies whose F-functions have only one positive lobe which contributes to the bow shock overpressure. The second equation can be used to calculate a detailed pressure signature and can be used in conjunction with any F-function.

In the last section of the paper Whitham performs a check on his theory by computing the wave drag on a body. The drag turns out to be expressed very simply in terms of the F-function by the equation

$$D = \pi\rho_o U^2\int_0^\infty F^2(y)dy$$

The fact that this equation can be reduced to the usual von Karman double integral constitutes a very good check on the theory.

This paper deals only with the contribution of body volume to the sonic boom. In a later paper (see capsule summary P-14) Whitham treats the lift contribution to the boom strength. Lift effects are also treated later by Walkden (see capsule summary G-6).

This is the most fundamental reference in the area of sonic boom generation. It also provides the starting point for present-day real-atmosphere propagation theory.

G-4
HIGHER APPROXIMATIONS IN AERODYNAMIC THEORY
M. J. Lighthill
General Theory of High Speed Aerodynamics, Sect. E
Princeton University Press; 1954

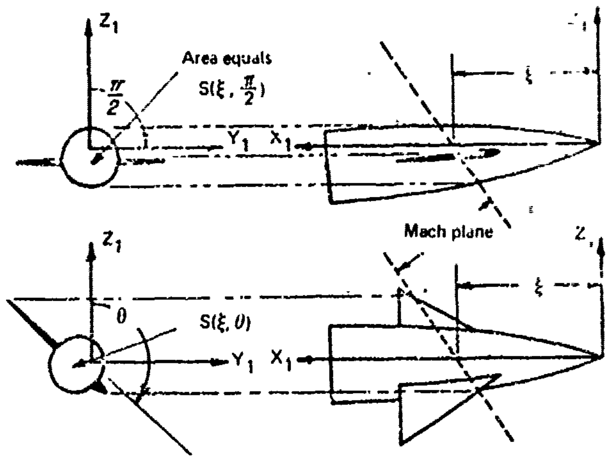
The section in this book having direct application to sonic boom theory is section E-6, entitled "Supersonic Projectile Theory: Complete Flow Pattern." This is a recapitulation of Whitham's "Flow Pattern of a Supersonic Projectile" and the reader is referred to the summary G-3 of that paper for details of this theory.

Lighthill's physical descriptions of various aspects of the theory take a somewhat different viewpoint than those in Whitham's paper. For this reason it is a worthwhile paper to review in conjunction with the latter to obtain an in-depth understanding of the theory which constitutes the basis of all sonic boom calculations.

G-5
THE WAVE DRAG OF ARBITRARY CONFIGURATIONS IN LINEARIZED FLOW AS DETERMINED BY AREAS AND FORCES IN OBLIQUE PLANES
Harvard Lomax
NACA RM A55A18, 1955

Linear theory is used to show that the wave drag of an arbitrary body in steady supersonic flow can be determined from the average wave drag of a series of equivalent bodies of revolution. The direct relevance of this paper to sonic boom theory lies in the derivation of these equivalent bodies.

Lomax shows that, for any given azimuthal angle θ, a body of revolution which is equivalent to the volume effects of the airplane can be found in the following manner: Consider a point at a large distance from the body whose azimuthal angle with respect to the airplane is θ. Now consider the plane tangent to the forward-facing Mach cone from that point. The point of tangency is the point of intersection of the Mach cone with the x-axis. (The x-axis passes through the nose of the body and is parallel to the flow direction.) The intersection of this oblique plane with the body defines a certain area. The projection of this area onto a plane normal to the free stream defines another area, $S(\xi,\theta)$, where ξ is the value of the x coordinate at the point of intersection. By passing oblique planes parallel to the original plane through each point of the body, a complete area distribution $S(\xi,\theta)$ is swept out, this being the area distribution of the equivalent body of revolution. As the form of $S(\xi,\theta)$ indicates, there will, in general, be a different equivalent body for each angle θ. This is illustrated in the figure below.



Determination of equivalent body area distribution for volume effects

The body of revolution equivalent to the lift effects of the airplane is found in the following manner. For a given angle θ, oblique cutting planes are again passed through the body. Then $l(\xi,\theta)$ is defined as the lift (the vertical component of the net resultant force, positive upward) on a given section. Lomax shows that the rate of change of the cross-sectional area of the equivalent body of revolution for lift is:

$$S'(\xi,\theta) = \frac{1}{q\,U_o}\,l(\xi,\theta)$$

where q is the free stream dynamic pressure and U_o is the free stream speed. The equivalent body of revolution for the entire airplane is then given by the sum of the equivalent bodies for the lift and volume.

Several examples are then given of the application of the theory. These examples include finding the wave drag of a plane wing, a Busemann-type biplane, and a shrouded body of revolution.

This paper provides a good illustration of the application of Hayes' supersonic area rule for both the volume and the lift contributions to the flow field surrounding an airplane.

G-6
THE SHOCK PATTERN OF A WING-BODY COMBINATION, FAR FROM THE FLIGHT PATH
F. Walkden
Aeronautical Quarterly, Vol. IX, part II, May 1958, pp. 164-194

In this paper Walkden uses Whitham's theory to calculate the strength and position of the front shock far from the flight path of a wing-body combination. The effects of wing thickness, lift, and wing-body interference are included.

It is assumed that the body is axisymmetric, with the main stream direction as the axis of symmetry. The wing may be inclined at a small angle to the main stream.

The potential field of the wing-body combination is due to four different contributions: the potential field of the body of revolution, the potential of the symmetric thickness of the wing, the potential due to lift, and the interference potential between the wing and the body. Walkden looks at each of these potentials separately. He starts with the value given for each by linear theory and corrects it using Whitham's theory, which involves replacing the approximate characteristics of the linear theory by a more accurate representation. These expressions for the potentials are then simplified by making a large distance approximation.

In determining the interference potential, Walkden neglects all interference effects except that which arises from the flow over the wing at zero incidence at the surface of the body. To determine this interference potential the component of velocity normal to the surface of the body due to the potential field of the wing is determined, and an interference potential is found which will cancel this.

The component of the axial perturbation velocity u (x axis in direction of flow, origin at nose of body) due to each of the four velocity potentials, ϕ, is given by ϕ_x. Knowing u, the F-functions of each of the four components at large distances from the body are determined from

$$u = \frac{-F(\tau,\theta)}{\sqrt{2Br}}$$

where $B = \sqrt{M^2 - 1}$

x, r, θ are polar coordinates and $\tau(x,r)$ describes the characteristic curves

Once the F-functions are known it is a simple matter to calculate the position and strength of the shock which would result from any of the four components by itself or from the entire wing-body combination. The strength of the shock is given in terms of the F-function by Whitham's general equation (see capsule summary G-3). An equation for the position of the shock in terms of the F-function is determined using the "angle property." According to this property the shock is placed at the intersection of the corrected characteristics in such a manner that the angle of intersection is bisected.

Substituting the appropriate F-function into these two equations gives the strength and position of the shock. The F-function of the entire wing-body combination is merely the sum of the four component F-functions, which are as follows:

Lift: $$F(\tau,\theta) = -\frac{\beta\sin\theta}{4\pi}\int_0^\tau \frac{s_3''(t)}{\sqrt{\tau-t}}\,dt;$$

$$s_3'(t) = \int_{\beta_1}^{\beta_2} \frac{\Delta P(\alpha,\beta)}{1/2\,\rho_\infty U_\infty^2}\,d\beta$$

Wing Thickness: $$F(\tau,\theta) = \frac{1}{2\pi}\int_0^\tau \frac{s_2''(t)}{\sqrt{\tau-t}};$$

$$s_2'(t) = 2\int_{\beta_1}^{\beta_2} z_\alpha\,d\beta$$

Interference: $$F(\tau,\theta) = \frac{1}{2\pi}\int_0^\tau \frac{s_1''(t)}{\sqrt{\tau-t}}\,dt;$$

$$s_1''(t) = -4\,R(t)\,h'(t)$$

Body: $$F(t) = \frac{1}{2\pi}\int_0^\tau \frac{s''(t)}{\sqrt{\tau-t}}\,dt$$

where α, β are distances in the x-, y-directions measured from a point on the supersonic leading edge of the wing

$z(x,y)$ = thickness distribution of the wing
$h(x) = z(x,0)$
$R(x)$ = radius distribution of body

β_1 and β_2 are the ordinates of the points of intersection of the appropriate oblique cutting plane as determined by the supersonic area rule (see capsule summary G-1) and $\Delta P/(1/2\,\rho_\infty U_\infty^2)$ is the local lift coefficient.

The functions $s(t)$, $s_1(t)$, $s_2(t)$, and $s_3(t)$ give the area distributions of the bodies of revolution which are equivalent to the body, interference, thickness, and lift effects, respectively. The equivalent body of revolution for the entire wing-body combination is given by the sum of these four components.

The paper then goes on to discuss nonuniform motion. For these results, see capsule summary P-18.

This reference is an important one in generation theory since, along with a paper of Whitham's (see capsule summary P-14), it forms much of the basis for the theory concerning lift effects on sonic booms. It is also significant for its combination of the results of Whitham and Hayes into a unified theory.

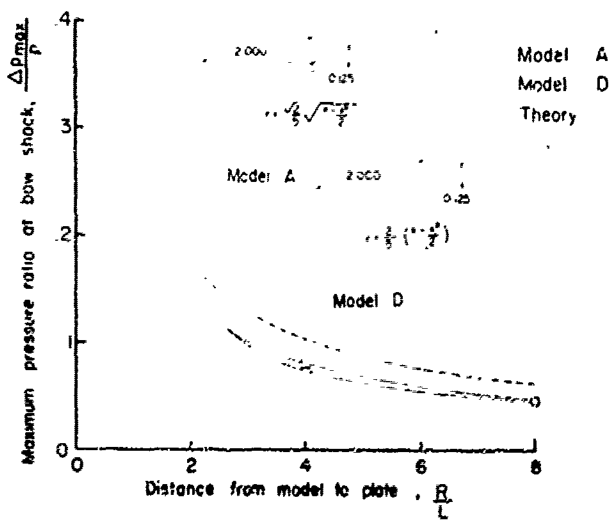
G-7
AN INVESTIGATION OF SOME ASPECTS OF THE SONIC BOOM BY MEANS OF WIND-TUNNEL MEASUREMENTS OF PRESSURES ABOUT SEVERAL BODIES AT A MACH NUMBER OF 2.01
Harry W. Carlson
NASA TN D-161, December 1959

This paper presents the results of an experimental investigation into the validity of the theories of Whitham and Hayes (see capsule summaries G-3 and G-1). To a lesser extent, Walkden's theory concerning the effect of lift on sonic boom is also investigated.

Seven models having a variety of shapes and sizes were tested in the NASA-Langley 4x4 foot supersonic wind tunnel at a Mach number of 2.01 and a Reynold's number of 2.5 x 10^6 per foot.

The relative size of the tunnel and models permitted measurements at 8 body lengths distant from five of the models and 32 body lengths from the smallest model. Whitham's asymptotic formula (see capsule summary G-3) for the bow shock overpressure was used to compare the measured values of shock strength with theoretical values.

The results showed that the volume-induced far-field overpressure and its attenuation with distance is "adequately" estimated (within 25%) by Whitham's theory (see figure below). It was also shown that nonaxisymmetrical shapes may be replaced by equivalent bodies of revolution in estimating far-field pressures, as predicted by Hayes' supersonic area rule. A further validation of Hayes' theory was found in the dependence of the equivalent body on the azimuthal position of the field point.



Comparison of theory and experiment

In connection with lift effects it was found that the lift-induced pressures attenuated at a more rapid rate than volume-induced pressures near a wing. But in the far field it was found that lift-induced pressures attenuated at the same rate as the volume pressures. Lift-induced pressures calculated using Walkden's theory showed "useful" correlation with the measured data.

The positions at which the pressures were measured were actually not far enough from the models to be in the far-field, as shown by Kane in a later paper (see capsule summary G-14). This may perhaps account for the slight discrepancy between measured and theoretical overpressures. The overall conclusions of the report are still valid, however.

G-8

SUPERSONIC BOOM OF WING-BODY CONFIGURATIONS

I. L. Ryhming and Y. A. Yoler

IAS 28th Annual Meeting Paper No. 60-20, Jan. 1960

Also, Boeing Document D1-82-0034, 1959

This is, basically, a "minimization" paper, since its main purpose is to investigate the possibility of reducing the sonic boom due to lift by making use of the interference between a wing and body (for a discussion of these results see capsule summary M-3 in the "Minimization" section of this document). It is also significant in generation theory, since the experimental results obtained tended to confirm the validity of Walkden's theory concerning the effects of lift and wing-body interference on sonic boom generation.

The author makes use of the expressions derived by Walkden (see capsule summary G-6) for the F-functions and equivalent bodies of revolution for the body volume, wing volume, lift, and wing-body interference to derive a method of contouring the body so that the pressures on the wing interfere favorably with those on the body. Wind tunnel tests confirm that the body designed using this method does reduce the boom due to lift (see capsule summary M-3 for an illustration of this), thus indicating that the theory derived by Walkden is valid.

This was one of the first papers to experimentally investigate lift and interference effects on sonic boom generation.

G-9

GROUND MEASUREMENTS OF AIRPLANE SHOCK-WAVE NOISE AT MACH NUMBERS TO 2.0 AND AT ALTITUDES TO 60,000 FEET

Lindsay J. Lina and Domenic J. Maglieri

NASA TN D-235, March 1960

Sonic boom measurements near the ground track for flights of an F-8 supersonic fighter weighing 30,000 pounds and one flight of a B-58 supersonic bomber weighing 140,000 pounds are presented. The purpose of these measurements was to check the theories of Whitham and Randall concerning generation and propagation, respectively.

The following equation, which was presented in NASA Memo 3-4-59L (see capsule summary S-2) and which is a modification of Whitham's asymptotic equation, was used to predict the sonic boom overpressure:

$$\Delta P_o = K_1 K_2 \frac{\sqrt{P_A P_o}}{y^{3/4}} (M^2-1)^{1/8} \left(\frac{d}{\ell}\right) \ell^{3/4}$$

where

ΔP_o = pressure rise across shock wave at ground level

K_1 = ground reflection factor

K_2 = airplane body shape factor

P_a = ambient pressure at altitude, lb/sq ft

P_o = ambient pressure at ground level, lb/sq ft

y = perpendicular distance from measuring station to flight path, ft

M = airplane Mach number

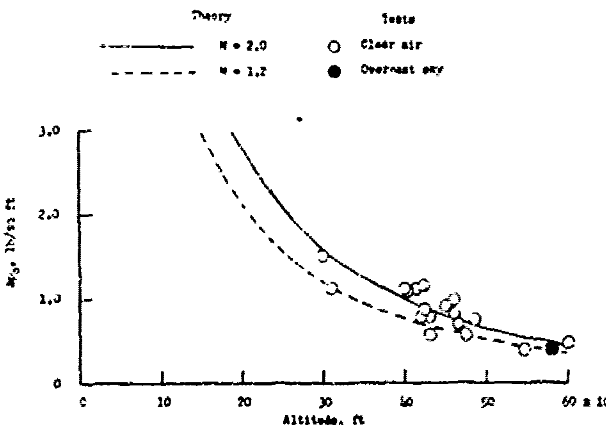
d = equivalent body diameter, ft

ℓ = airplane length, ft

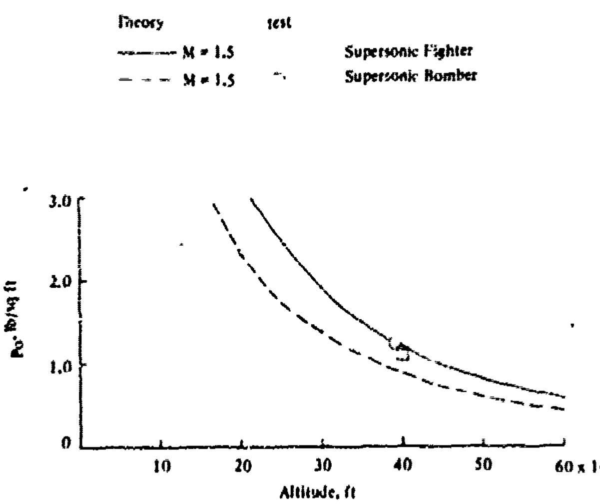
This equation takes into account the effect of altitude, Mach number, and airplane shape and length, but it does not include lift effects.

It was found that the effect of Mach number on the ground overpressure was small in the Mach number range from 1.4 to 2.0, which was in good agreement with theory. It was also found that there were only minor differences between the overpressure due to the fighter and that due to the bomber for both at a Mach number of 1.5 and an altitude of 40,000 feet, indicating that the effect of airplane weight and length was not very important at this altitude.

Fairly good agreement was obtained between theoretical and measured values of the overpressures for both the fighter and the bomber, as shown in the figures below, which were taken from this paper.



Comparison of theoretical and measured overpressures for fighter



Comparison of theoretical and measured overpressures for bomber

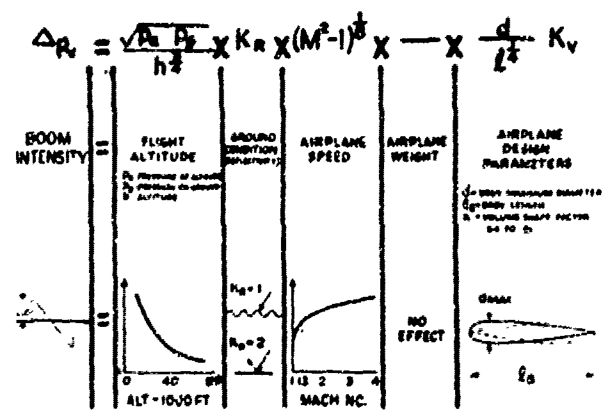
This investigation deals with sonic boom volume theory. In a later investigation (see capsule summary G-16) Maglieri and Hubbard investigate lift effects on the sonic boom using flight measurements.

This was the second attempt to verify sonic boom theory using flight measurements. The first was by Mullens (see capsule summary G-73). The present investigation was the more extensive of the two.

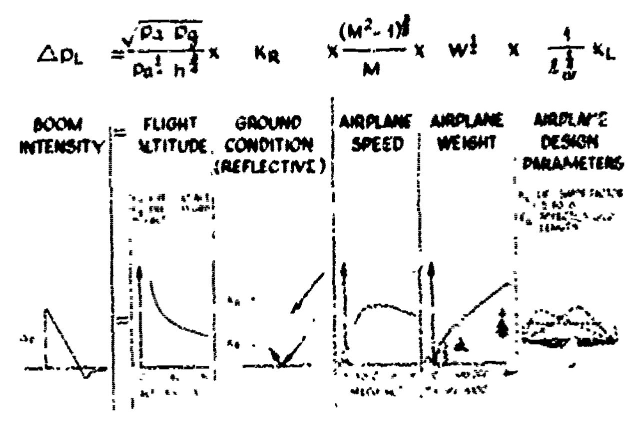
G-10
LIFTING EFFECTS IN SONIC BOOM
Boeing Airplane Company
Document No. D6-5845, September 30, 1960

This document summarizes the effect of lift on the sonic boom of an airplane, the manner in which the lift is related to the volume term, and the effect of aircraft design parameters.

It is basically a simplified, illustrative version of the paper described in capsule summary G-11. The reader is referred to that capsule summary for a brief review of significant findings. The figures below, which were taken from this paper, summarize the manner in which airplane configuration parameters and flight conditions affect the sonic boom intensity.



Volume contribution



Lift contribution

This document is very clearly and concisely written and provides a good quick introduction to lift effects and to the influence of various parameters on the far-field asymptotic sonic boom characteristics.

G-11

AN INVESTIGATION OF LIFTING EFFECTS ON THE INTENSITY OF SONIC BOOMS

John Morris

Journal of the Royal Aeronautical Society, Vol. 64, No. 598, Oct. 1960, pp. 610-616

This paper investigates the relative importance of lift and volume effects in sonic boom generation. The results are limited to steady level flight, and the overpressure is evaluated only at points along the aircraft's ground track.

Whitham's equation for the asymptotic shock strength of a body of revolution (see capsule summary G-3) is used to compute the sonic boom overpressure. The separate effects of lift and volume come into this equation through the F-function, since

$$F(x) = F(x)_{vol} + F(x)_{lift} = \int_0^x \frac{S_A''(t)}{2\pi} (x-t)^{-1/2}\, dt + \int_0^x \frac{B\ell'(t)}{4\pi q} (x-t)^{-1/2}\, dt$$

where

$B = (M^2-1)^{1/2}$, $q = \frac{1}{2}\rho V^2$

$\ell(x)$ = lift/foot distance along the wing centerline

t = distance from nose of fuselage

x axis is aligned with flow direction, origin at nose of body and S_A'' is the second derivative of the aircraft (wing + fuselage + tail, etc.) cross-sectional area as determined by the supersonic area rule (see capsule summaries G-1, G-5, and G-6). (For further information on the F-function see capsule summaries G-3 and G-6.)

The contributions of lift and volume to the overpressure are then separated and the notation simplified to give:

$$\Delta P_V = 0.429\, K_R K_A K_V\, (M^2-1)^{1/8} \frac{S_{AM}^{1/2}}{\ell_A^{3/4}}\, h^{-3/4}$$

$$\Delta P_L = 0.305\, K_R K_A K_L \frac{(M^2-1)^{3/8}}{M}\, W^{3/8} \left(\frac{W}{S} AR\, \mu^2\right)^{1/8} \rho_a^{-1/2}\, h^{-3/4}\, P_g$$

where

S_{AM} = maximum aircraft normal cross-sectional area

AR = aspect ratio

$\mu = C_R/\ell_W$

C_R = wing root chord

ℓ_W = distance (ft) from wing apex to rear tip edge

h = airplane altitude

P_g = ground level pressure

ℓ_A = length of aircraft (ft)

K_R = reflectivity factor

K_A = attenuation factor which accounts for real atmosphere effects

K_V = volume shape factor

K_L = lift shape factor

K_V depends only on the shape of the body and not on its length or fineness ratio. For practical airplane shapes K_V should lie between the approximate limits 1.5 ~ 2.0. K_L varies in practice between 1.4 ~ 1.63.

In order to take into account lift-volume interaction, the complete F-function for the airplane must be computed. Noting that the evaluation of the F-function can be very tedious for practical wing-body combinations, Morris suggests a method of estimating the overpressure. This method is limited to configurations in which the wing is located toward the rear of the body, since most supersonic airplanes are of this type. The simple rule is

$$\Delta P_{combined} = \Delta P_V \text{ or } \Delta P_L \text{ whichever is greater.}$$

The reason that Morris suggests this rule is that below a certain altitude, which is determined by the airplane characteristics, the boom intensity is not affected by lift. Above this altitude the lifting term is considerably larger than that due to body shape. For an illustration of this see capsule summary G-10.

The altitude above which lift becomes important is then evaluated for various airplane types, and it is concluded that lift will dominate the sonic boom intensity of most aircraft at high altitudes and over most of the altitude range for large aircraft.

As pointed out by the author, at the time this paper was written, calculation of F-functions was extremely cumbersome. However, this is not the case today due to the use of sophisticated computer programs. The work done here is still valid, however, for making rapid estimates of sonic boom overpressures. These estimates are probably within 20-50% of actual values which might be calculated using current methods (depending on the configuration).

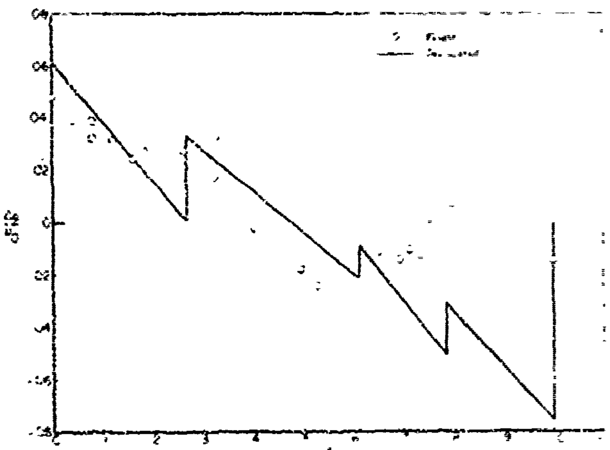
The effect of lift on boom strength was usually neglected in calculations made at the time this paper was written. The results presented in this paper made it easier for subsequent investigators to determine whether or not the neglect of lift effects was justified.

G-12

EXPERIMENTAL AND CALCULATED FLOW FIELDS PRODUCED BY AIRPLANES FLYING AT SUPERSONIC SPEEDS
Harriet J. Smith
NASA TN D-621, November 1960

Results are presented in this paper of an experimental check on Whitham's theory in the near field. The pressure signatures resulting from supersonic flights of an F-100, an F-104, and a B-58 airplane were measured by a sensitive pressure transducer mounted on the nose boom of another airplane passing at a given distance. The measured pressure signatures were then compared with detailed signatures calculated using Whitham's general equation for the overpressure (see capsule summary G-3). The asymptotic far-field expression for the overpressure was not used, since the measurements were made at distances from 120 to 425 feet.

The results showed that the strength of the bow shock wave and the overall characteristics of the flow field were fairly well estimated by theory. However, the location and magnitudes of all of the intermediate shocks were not accurately predicted. It was also found that using an equivalent body of revolution based on the area intercepted by parallel planes swept at the Mach angle greatly improved the results of the calculations over those based on a normal-area distribution equivalent body. This is illustrated in the two figures below, which were taken from this paper.



B-58 pressure signature based on normal area distribution

Calculated B-58 pressure signature based on Mach line area distribution

Lina and Maglieri (see capsule summary G-9) presented measurements in an earlier paper of the far-field bow shock overpressures of a fighter and bomber which, essentially, confirmed Whitham's theory in the far-field. This paper serves the same purpose for the near-field region of the flow.

Lift effects on the boom strength are neglected in this paper, which was the normal practice at the time it was written. Whether this neglect was justified or not cannot be determined from the paper, since the altitudes at which the flights were made is not given.

The appendix gives a numerical method of constructing the $F(y)$ curve using the first derivative of the cross-sectional area distribution.

This was the first flight investigation of the flow field near the airplane. It was also one of the first investigations in which detailed theoretical pressure signatures were compared with measured signatures rather than comparing only the bow-shock overpressure. The most important finding was that the normal-area distribution normally used in the theory at that time may not always be an adequate representation of an equivalent body of revolution for estimating the entire flow field, especially at Mach numbers much greater than 1. For these cases it was found that the area distribution determined by using the oblique cutting planes of the supersonic area rule (see capsule summary G-1) must be used.

G-13

CALCULATED EFFECTS OF BODY SHAPE ON THE BOW-SHOCK OVERPRESSURES IN THE FAR FIELD OF BODIES IN SUPERSONIC FLOW
Donald L. Lansing
NASA TR R-76, 1960

This paper presents a theoretical analysis of the effect of body geometry on the asymptotic sonic boom strength of a body of revolution. Its purpose is to evaluate

$$\int_0^{y_o} F(\eta)\, d\eta$$

(see Whitham's asymptotic formula in capsule summary G-3) for a family of bodies of revolution. A body shape constant is derived which makes it unnecessary to evaluate the F-function explicitly to determine the sonic boom strength.

As can be seen in capsule summary G-3, Whitham's asymptotic formula for the pressure jump across the bow shock is proportional to

$$\sqrt{\int_0^{y_o} F(\eta)\, d\eta}$$

where

$F(y)$ is the Whitham F-function

η is a dummy variable of integration

and y_o = value of y which makes integral a maximum.

The only portion of this expression which is dependent upon body geometry is the integral. Randall (see capsule summary P-21) evaluated this integral for a parabolic body of revolution in terms of its length and maximum cross-sectional area. Maglieri and Carlson (see capsule summary S-2) in "Survey" section) modified Randall's results by including a "body shape factor" in the expression for the overpressure. This body shape factor was evaluated for three bodies of revolution having differing locations for their maximum cross-sectional area. Lansing uses numerical integration to derive an expression for the body shape constant for an arbitrary body of revolution, thus extending the method of Maglieri and Carlson and making it more exact. The resulting expression involves only the cross-sectional area and can be readily evaluated for body shapes for which no analytical expression is available.

Lansing's final expression for the overpressure is:

$$\frac{\Delta P}{P_\infty} = \frac{\beta^{1/4}}{(r/\ell)^{3/4}} \frac{2 R_{max}}{\ell} C_b$$

where

$$C_b = \frac{\gamma \sqrt{\pi}}{2^{3/4}\sqrt{\gamma+1}} \sqrt{\bar{I}_{max}},$$

$$\bar{I}_{max} = \frac{\sqrt{\ell}}{S_{max}} I_{max},$$

$$I_{max} = \int_0^{Y_o} F(\eta)\, d\eta$$

ℓ = body length

R_{max} = maximum body radius

S_{max} = maximum cross-sectional area

The body shape constant C_b is then evaluated for a number of families of body shapes chosen to investigate the effects of nose angle, fineness ratio, and location of maximum cross section on the bow shock overpressures.

Lansing concludes that the body geometry influences the far-field pressure, to first order, only through the fineness ratio. Local details have second order effects which, in general, can only be accounted for by direct computation of the body shape constant. It was found that this constant usually lies somewhere between 0.5% and 0.81, which agrees with Maglieri's results.

The method derived by Lansing in this paper to determine the influence of body geometry without actually evaluating the F-function provided one of the best early methods of computing the asymptotic bow shock overpressure.

G-14

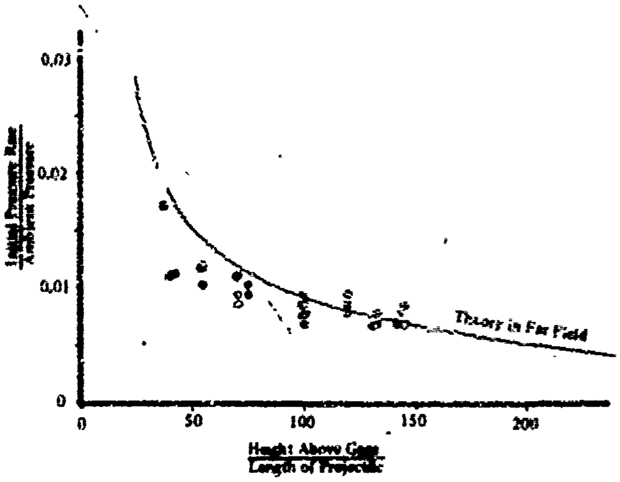
DETERMINATION OF THE FAR FIELD FROM BALLISTIC RANGE SONIC BOOM TEST DATA

Edward J. Kane
Boeing Airplane Company, Document No. D6-7165
February 8, 1961

The investigation presented in this paper had two purposes. The first was to determine the feasibility of using ballistic tests to investigate sonic boom theory. The second was to establish the point in the flow-field of a supersonic projectile at which the far-field of Whitham's theory begins.

The flow field around a body moving supersonically may be divided into three regions. These are known as the local field (near the body surface), the near field, and the far field. In the near field the effect of body shape on the boom intensity is a variable dependent on the distance from the body, while in the far field the effect of the body shape does not vary with distance.

The procedure used to determine the far-field boundary consisted of firing a bullet from a rifle at a given distance above a pressure transducer. The height of the bullet's path above the measuring station was then varied to determine the effect of distance on the measured signature. The measured overpressures and signature lengths were then plotted versus distance from the flight path, along with theoretical asymptotic far-field curves calculated using Whitham's theory. The distance at which the measured values began to fall approximately on the theoretical far-field curves was taken to be the beginning of the far-field. This distance turned out to be approximately 100 body lengths from the projectile flight path, as shown in the figure below. It was also found that this result was not affected significantly by the slenderness of the body.



Determination of far-field boundary

To further define the limits of the various flow-field regions, flight data compiled by Smith (see capsule summary G-12) was used to determine the "near-field" minimum boundary. This was found to be at about four body lengths from the flight path.

This investigation did demonstrate the feasibility of using ballistic tests to investigate sonic boom theory. Some difficulties were encountered, however. The biggest drawback was found to be the short duration and low intensity (on the order of .20 psi) of the pressure signature. This meant that the measuring instruments had to be extremely sensitive and thus subject to the influence of outside disturbances.

Whitham and Lighthill had concluded, on the basis of experimental data by DuMond, Cohen, Panofsky, and Deeds (see capsule summary P-2) that the boundary of the near- and far-fields was at about 100 projectile lengths from the body centerline. This is the same conclusion reached in this investigation using more sophisticated experimental techniques. The difference, however, was that Whitham and Lighthill were dealing with bodies whose slenderness ratio was of the order of 10, while for the bodies used in this investigation it was about 3.6. This is significant in that the latter body is not, strictly speaking, a slender body. This experimentally verified the fact that Whitham's results, even though derived for a slender body, are, at large distances, applicable to fairly bluff bodies.

The determination of the locations of the local, near-, and far-field boundaries made in this paper provided a valuable aid in subsequent investigations into the factors affecting sonic booms. Many previous investigations had used Whitham's asymptotic expression for the overpressure at locations too close to the flight path for "far-field" conditions to exist (see capsule summary G-7, for example). The results of this investigation made it much easier to determine when the "far-field" equations could be used.

G-15

AN INVESTIGATION OF THE INFLUENCE OF LIFT ON SONIC-BOOM INTENSITY BY MEANS OF WIND-TUNNEL MEASUREMENTS OF THE PRESSURE FIELDS OF SEVERAL WING-BODY COMBINATIONS

Harry W. Carlson

NASA TN [illegible], July 1961

This paper presents the results of an experimental check on the theories of Walkden and Morris (see capsule summaries G-6 and G-11) concerning the effect of lift on sonic boom intensity.

Four models one-half inch in length were tested in the NASA-Langley supersonic wind tunnel at a Mach number of 2.01 and a Reynolds number of $[illegible].5 \times 10^6$ per foot. The relative size of the tunnel and models made it possible to obtain signatures which approached the far field N-wave.

The effect of lift was determined by testing each of the models at angles of attack of 0°, 5°, and 10°. The wing areas of the models varied from 0.014 to 0.144 square inches, providing a [illegible] indication of the effect of lift.

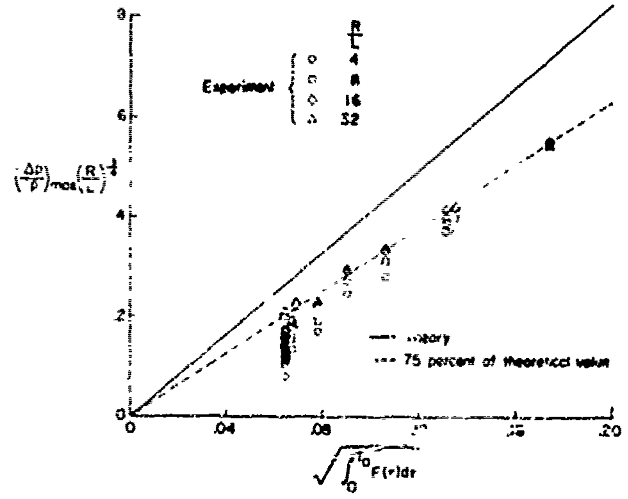
The equation used to compute the bow-shock overpressure is the same as Whitham's asymptotic equation (see capsule summary G-3) except for the inclusion of a reflection factor which is 1 for free air and 2 for a smooth flat plate. The F-function used in this equation is the same as that derived by Walkden (see capsule summary [illegible]) except that interference effects are not taken into account here. In general, the volume and lift effects are combined in the F-function before pressures are found. However, in this case, due to the fact that the F-functions had the same limits of integration and were everywhere positive, the pressure rise due to the volume and lift was expressed as

$$\left(\frac{\Delta P}{P}\right)_{total} = \sqrt{\left(\frac{\Delta P}{P}\right)^2_{vol} + \left(\frac{\Delta P}{P}\right)^2_{lift}}$$

A numerical approach was used to obtain the F-functions because of difficulties associated with analytical treatment of the volume contributions to the F-functions for the models used here. This method is essentially the same as that described in capsule summary G-23.

In this investigation the normal cross-sectional area of the wing-body combination was used rather than the more rigorously correct area determined by the supersonic area rule. The error involved in making this approximation was checked and found to be small. The models were designed so that the normal cross-sectional area distribution was the same for each. Thus the contributions of the volume to the F-function was the same for all models. See capsule summary G-23 for an illustration of the manner in which the F-function was derived.

The results showed that the effect of lift did, as expected, increase with increasing angle of attack and with increasing wing area. For the model with maximum wing area the maximum overpressure increased by a factor of about 2.5 when the angle of attack was increased from 0° to 10°. For the model with the minimum wing area the maximum overpressure increased by a factor of approximately 1.8 for the same change in angle of attack. The experimental curves of bow-shock overpressure versus angle of attack follow the same trend as the theoretical curves, but the measured values are consistently only about 75% as large as the theoretical values (see figure below). This discrepancy was attributed to factors in the experimental system which tended to reduce the measured peak values of the pressure rise such as vibration of experimental apparatus, unsteady or turbulent flow, and boundary layer effects on pressures at the measuring surface.



Comparison of theoretical and experimental overpressures

An examination is then made of previously published flight test data to determine lifting effects. The results are inconclusive because of the large scatter in the flight test date. The wind tunnel results are not invalidated, however.

This investigation provided the first experimental verification of the validity of the theory concerning lift effects on sonic boom intensity.

G-16

GROUND MEASUREMENTS OF THE SHOCK-WAVE NOISE FROM SUPERSONIC BOMBER AIRPLANES IN THE ALTITUDE RANGE FROM 30,000 TO 50,000 FEET

Domenic J. Maglieri and Harvey H. Hubbard

NASA TN D-880, July 1961

The main purpose of this investigation was to determine how important lift effects are on the sonic boom of large airplanes at high altitudes. To accomplish this, pressure signatures from a B-58 weighing between 83,000 and 120,000 pounds were measured. The flights were made at Mach numbers of 1.24 to 1.52 in the altitude range from 30,000 to 50,000 feet. The measured overpressures were then compared with those calculated using Whitham's expression for the overpressure due to volume, Morris' expression (see capsule summary G-11) for the overpressure due to lift, and an expression derived by Carlson for the combined lift-volume overpressure (see capsule summary G-15).

The measured pressures were generally higher than would be predicted by the theory which accounts for only volume effects. The agreement is much better when combined lift-volume theory is used. It is concluded, as a result of this, that lift effects may be significant for large airplanes flying at altitudes above 30,000 feet. This agrees with the predictions made by Morris.

Prior to this paper numerous measurements had been made of ground pressures resulting from fighter airplanes at Mach numbers up to 2 and at altitudes to 60,000 feet (see capsule summaries G-9 and P-20). This paper provided complementary data for large airplanes.

G-17

NOTE ON SOME THEORETICAL ASPECTS OF LIFT PRODUCED SONIC BOOM

Armand Sigalla

Boeing Airplane Company, Document No. D6-7996, 1961

In this paper the transfer of weight from a lifting wing in supersonic flow to the ground is investigated. Also, a formula for the F-function of a wing with discontinuities in the chordwise lift distribution is derived.

The author begins with a review of Whitham's theory. An expression is then derived for the perturbation potential at large distances from the wing in terms of the lift distribution. Use is made of Hayes' area rule as in the manner of Heaslet, Lomax, and Spreiter (see capsule summary G-2).

From this a formula for the axial perturbation velocity in terms of the lift distribution is derived. The F-function for a wing having discontinuities in its lift distribution is then evaluated. The resulting expression for this F-function is:

$$F(y) = \frac{-(M^2-1)^{1/2} \sin\theta}{2\pi U_\infty} \int_0^y \frac{dh(\zeta)}{\sqrt{y-\zeta}}$$

where $h(\zeta)$ is a continuous differentiable function related to the lift distribution and the rest of the notation is the same as that defined in capsule summary G-3. The author points out that a discontinuous lift distribution may be thought of as a source distribution with discontinuous strength but the latter cannot be used to represent a body with discontinuous slopes. Thus a lift distribution of this type cannot be related directly to an equivalent body of revolution.

The transfer of lift to the ground is shown in a straightforward manner by integrating the full linear theory pressure coefficient at ground level over the entire ground area affected by the airplane. The pressure coefficient is related to the previously derived axial perturbation velocity by $C_p = \frac{-2u}{U_\infty}$. The resulting force on the ground is, as expected, equal to the lift. It is important to note that no large-distance approximations are made.

This equality of lift to the reaction force on the ground cannot be explained using only Whitham's asymptotic theory. According to this theory the strengths of the front and rear shocks of a body of revolution are equal with the pressure decreasing linearly in between. This leads to no net force. Since, except for discontinuous lift distributions, the signature of a lift distribution is equivalent to that of a certain body of revolution, Whitham's theory would show that no force is transferred to the ground by a lifting wing. The author explains this paradox by pointing out that most applications of Whitham's theory are based on

asymptotic forms for the velocity perturbations. These forms are more valid in the vicinity of the shock waves than in the region between them. However, in order to determine the resultant of the pressures on the ground, the pressure field over the whole ground must be examined. The use of an asymptotic expansion which is more valid in some regions than in others is not permissible. The perturbation velocity used by the author is valid everywhere on the ground, however, thus accounting for the disparity between it and Whitham's theory in explaining the transfer of lift to the ground. The author concludes that the front lobe of the "N" wave must be somewhat larger than the rear lobe, including the pressure distribution following the rear shock wave. This is shown to be the case in a later paper by Seebass and McLean (see capsule summary G-38).

This paper was written with the aerodynamicist and not the mathematician in mind. As a result the mathematical derivations are explained in more depth than in most papers. The physical explanation of Whitham's theory given in the early part of the paper is very good.

G-18

WIND TUNNEL MEASUREMENTS OF THE SONIC-BOOM CHARACTERISTICS OF A SUPERSONIC BOMBER MODEL AND A CORRELATION WITH FLIGHT-TEST GROUND MEASUREMENTS

Harry W. Carlson

NASA TM X-700, July 1962

A one-inch model of a B-58 bomber was constructed and tested in the NASA-Langley 4x4 foot supersonic wind tunnel at a Mach number of 2.01. The measured pressure signatures were then compared with those obtained in previous B-58 flight test measurements and with those calculated using Whitham's asymptotic formula (see capsule summary G-3) and an F-function derived by Walkden accounting for both lift and volume effects.

The measured tunnel overpressures were consistently lower than those predicted by theory. This was thought to be due to experimental difficulties (see capsule summary G-15). The measured signatures were corrected to account for these effects by making the adjusted maximum overpressure equal to that found by dividing the area under the positive portion of the pressure signature by the characteristic length, which was defined as the distance from the half maximum pressure position on the pressure rise to the point of zero overpressure. After this adjustment was made the correlation between theory, tunnel results, and flight-test results was reasonably good, the greatest discrepancy occurring at the higher altitudes where the flight test measurements were about 20% higher than either the theory or the adjusted tunnel data. It was thought that part of this discrepancy might have been due to nonuniform atmosphere effects.

This investigation was the first to correlate theory, wind tunnel, and flight-test measurements. It demonstrated that either theory or wind tunnel data could be used with confidence to provide the estimates of sonic-boom characteristics.

G-19

LATERAL-SPREAD SONIC-BOOM GROUND-PRESSURE MEASUREMENTS FROM AIRPLANES AT ALTITUDES TO 75,000 FEET AND AT MACH NUMBERS TO 2.0

Domenic J. Maglieri, Tony L. Parrott, David A. Hilton, and William L. Copeland

NASA TN D-2021, August 1963

This paper presents the results of shock-wave overpressures measured for a wide range of altitudes and Mach numbers of fighter and bomber airplanes on the ground track and for lateral distances up to about 20 miles. It deals with both the generation and propagation of sonic booms, but only those parts of the report dealing with generation will be discussed here. The propagation results are summarized in capsule summary P-36.

The measurements showed that the fighter airplane data were in good agreement with volume theory in the vicinity of the flight track. For the bomber, however, measured data on the flight track were markedly higher than the values calculated by volume theory. These data included bow shock overpressure, signature length, and the magnitudes of the positive and negative impulses of the pressure signature.

These results demonstrated that lift effects were important for the bomber for a wide range of altitudes, but were much less important for the fighters. This had already been demonstrated in previous investigations (see capsule summaries G-9 and G-16). Thus this investigation, basically, just corroborated the results of previous investigations as far as generation of sonic booms is concerned. Its main contribution was in the area of propagation.

G-20

IN-FLIGHT SHOCK-WAVE PRESSURE MEASUREMENTS ABOVE AND BELOW A BOMBER AIRPLANE AT MACH NUMBERS FROM 1.42 TO 1.69

Domenic J. Maglieri, Virgil S. Ritchie, and John F. Bryant, Jr.

NASA TN D-1968, October 1963

The results of measurements of the pressure signatures above and below a B-58 supersonic bomber are presented in this paper. A pressure probe on the nose boom of a fighter airplane was used to make these measurements. The flight altitudes varied from 36,000 to 50,000 feet, the Mach number from 1.42 to 1.69, and the gross weight of the bomber from 83,000 to 117,000 pounds. The purpose of these tests was to obtain information concerning the way in which lift effects and volume effects combine in the generation of the shock-wave patterns from the generating airplane. The manner in which these lift and volume components combine had been shown by the theory of Walkden (see capsule summary G-6) and Morris (see capsule summary G-11) to be important, but it had not been verified experimentally.

The results showed that the signatures measured below the airplane had higher peak positive values than those measured above the airplane at comparable distances. Furthermore, it was found that below the airplane the higher over-

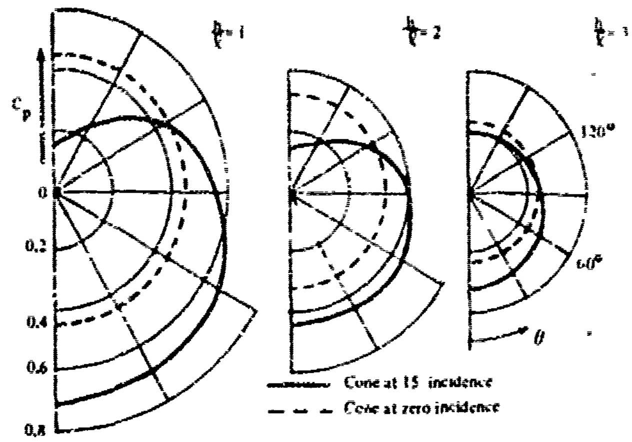
pressures were associated with the higher lift coefficients, whereas the reverse was true above the airplane. These results indicated that the lift pressures add to the volume pressures below the airplane and subtract from the volume pressures above the airplane.

Further results showed that for data obtained below the airplane the measured positive impulses were generally larger than the negative impulses, whereas the reverse was true above the airplane. Combined lift-volume calculations for the far-field using Walkden's theory and Carlson's method (see capsule summary G-23) were found to be in good agreement with the bow-shock pressure measurements made above and below the airplane, indicating that lift effects were significant for the operating conditions of these flights. The results also indicated that as the distance from the airplane increased the number of individual shock waves diminished until the classical N-wave shape was approximated at a distance of 50 to 90 body lengths for the conditions of these tests.

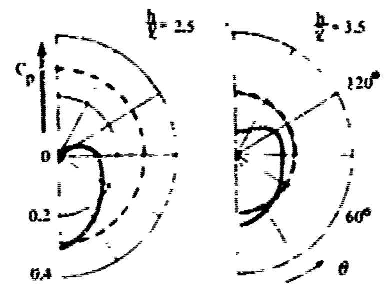
Lift effects on the sonic boom had been investigated previously in the wind tunnel by Carlson (see capsule summary G-15) and in flight tests by Maglieri and Hubbard and by Maglieri, Parrott, Hilton, and Copeland (see capsule summaries G-16 and G-19, respectively). This is the first investigation, however, which obtained data both above and below the airplane. This brought out the interaction of lift and volume effects much more clearly than in any of the previous papers. It is also important to note that only the theoretical bow shock overpressure was compared with the flight test results rather than a detailed pressure signature.

G-21
LIFT CONTRIBUTION TO THE SONIC BOOM
G. A. Bird and C. J. Wetherall
AIAA Journal, 2(3), 582-583, March 1964

This is a brief note which investigates the significance of the "circumferential evening" effect as a shock wave from a lifting body, whose strength varies in the azimuthal direction, propagates away from the configuration. Wind tunnel experiments were conducted at Mach 2 using a 15° semiapex angle cone and a flat delta wing with subsonic edges, which conventional theory indicated was equivalent to the cone at zero incidence. The results showed that for the cone at 15° incidence the variation of the shock strength in the azimuthal direction approached that of the same cone at zero incidence, as the distance from the model increased (see figure below). For the delta wing there was also a progressive evening of the shock strength around the periphery (see figure below), which, it is hypothesized, could cause the maximum shock strength from the wing to fall below the cone shock strength. It is concluded by the authors that, if the evening effect persists to large distances, it is likely that the Walkden-Whitham approach, which neglects it, could lead to a considerable overestimation of the sonic boom due to lift.



Shock strengths produced by 15 semiapex angle cone at M = 2



Comparison of shocks from slender delta and cone

The experimental results shown here are good, but the inability to obtain measurements in the far-field of the models makes it impossible to draw any definite conclusions as to the significance of the circumferential evening effect.

G-22
AN ANALYSIS AND CORRELATION OF AIRCRAFT WAVE DRAG
Roy V. Harris, Jr.
NASA TM X-947, March 1964

This paper presents and discusses a computer program developed by The Boeing Company which uses slender-body theory in combination with the supersonic area rule to find aircraft wave drag. The relevance to sonic boom theory lies in the numerical implementation of the supersonic area rule for calculating equivalent area distributions from descriptions of airplane geometry.

The supersonic area rule is reviewed and a computer program for calculating the area distribution of the equivalent body of revolution is described. The equivalent body area distributions are then calculated by solving for the normal projection of the areas intercepted by the appropriate Mach cutting planes.

This is a very valuable digital computer program, since the first step in all sonic boom calculations is to find the area distribution of the equivalent body of revolution.

G-23

GROUND MEASUREMENTS OF SONIC-BOOM PRESSURES FOR THE ALTITUDE RANGE OF 10,000 TO 75,000 FEET

Harvey H. Hubbard, Domenic J. Maglieri, Vera Huckel and David A. Hilton

NASA TR R-198, July 1964

Measurements were made of the pressure signatures of an F-104 fighter and a B-58 bomber airplane in the altitude range from 10,000 to 75,000 feet and at Mach numbers from 1.1 to 2.0. Calculations of the volume contribution to the boom strength were made using Whitham's asymptotic formula (see capsule summary G-3). Calculations which accounted for the combined effects of lift and volume were made using a numerical technique derived by Carlson, which is described in the appendix of this paper, based upon Walkden's theory (see capsule summary G-6).

Carlson's technique is in a form suitable for numerical calculations. In it the equation used to compute the bow shock overpressure is the same as Whitham's asymptotic formula (see capsule summary G-3) except for the inclusion of a reflection factor which is equal to 1 in free air and 2 for a smooth flat plate. The necessary inputs to the computation are a nondimensionalized area distribution A(t) formed by supersonic area rule cutting planes (see capsule summaries G-1 and G-5) and a nondimensionalized equivalent area distribution due to lift called B(t), which is given by

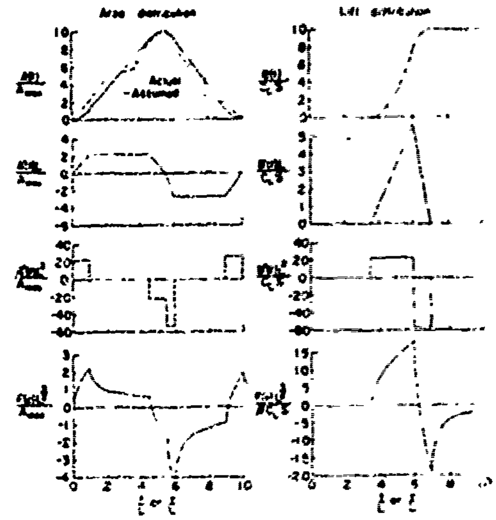
$$B(t) = \frac{\beta}{2q\ell^2}\int_0^x F_L' dx$$

where $\beta = \sqrt{M^2-1}$, q = free stream dynamic pressure, F_L' = lifting force per unit length along airplane longitudinal axis, t = nondimensionalized distance along longitudinal axis from airplane nose, x = distance measured along longitudinal axis from airplane or model nose, and ℓ = length of airplane in feet.

A combined area distribution $A_E(t)$ is formed by a direct addition of the A(t) and B(t) curves. The $A_E(t)$ curve is then approximated by a series of parabolic arcs having a first derivative composed of connected straight line segments and a second derivative composed of a step or pulse function (see figure below). The integral involved in the F(t) equation

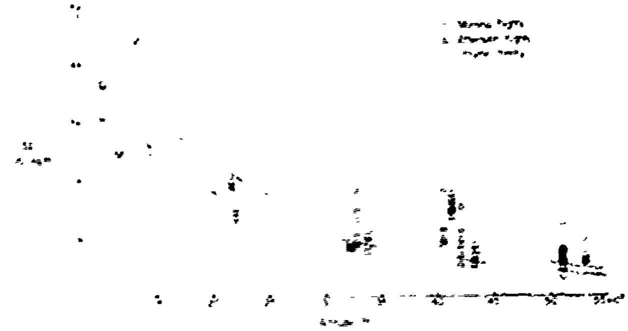
$$F(t) = \frac{1}{2\pi}\int_0^t \frac{A_E''(t)}{\sqrt{t-\tau}}\, dt$$

can be evaluated easily when $A_E''(t)$ is a constant, and by superposition a complete F(t) curve may be built up. An integration of the F(t) function to the point t_o (the value of t which maximizes the integral) is then used in evaluating the pressure rise characteristics. The degree of approximation of the $A_E(t)$ curve can be improved by increasing the number of pulses used.

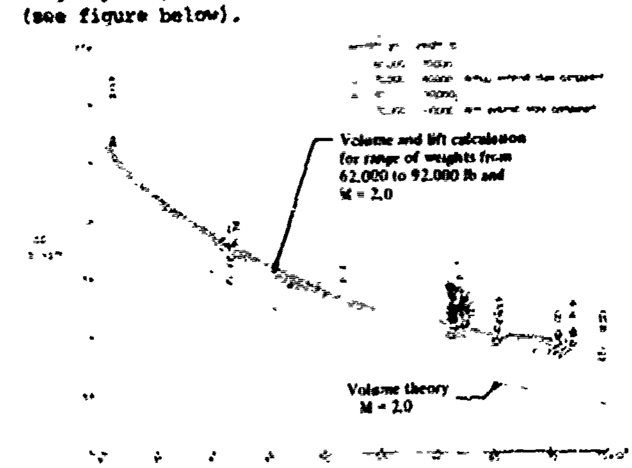


Development of volume and lift components for the F-function

The results showed that the calculated overpressures due to volume alone agreed fairly well with the measured overpressures of the fighter up to 40,000 feet, as shown in the figure below. Above this altitude the volume theory gives results which are lower than the measured values, indicating that lift effects are important for the fighter above 40,000 feet.


Overpressure vs altitude for fighter

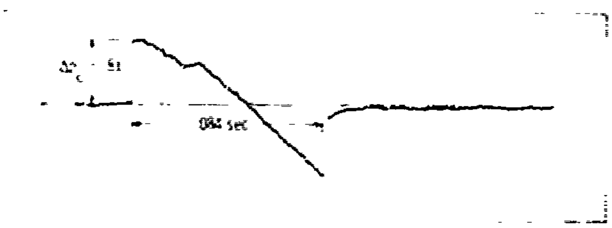
For the bomber, the volume theory results were too low at all altitudes above 30,000 feet. The volume-lift theory was in fairly close agreement with the measured overpressures, although slightly low, at all altitudes above 30,000 feet (see figure below).



Overpressure vs altitude for bomber

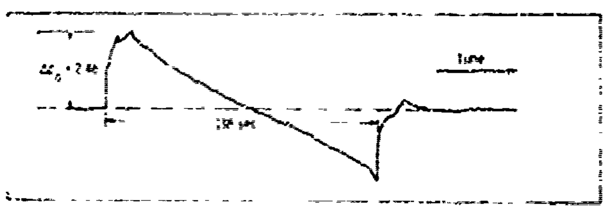
These results are in agreement with the theories of Morris (see capsule summaries G-11 and G-10) and the previously measured results of flight tests (see capsule summaries G-9, G-16, G-19, and G-20).

The instrumentation used in this test was more sophisticated than any used in previous tests up to that time. As a result, the actual pressure signatures were more faithfully reproduced than in any previous measurements. Typical measured signatures for the fighter and bomber are shown below.



Altitude, 52,200 feet; M = 1.5.

Pressure signature of bomber



Altitude, 31,200 feet; M = 1.5.

Pressure signature of fighter

G-24
WIND TUNNEL MEASUREMENTS OF THE FAR-FIELD PRESSURES DUE TO SOME LIFTING, SLENDER DELTA WINGS
T. A. Cook
C.P. No. 802, August 1964

This paper presents the results of an experimental investigation into the effects of lift and wing flow separation on sonic boom intensity.

Wind tunnel measurements were made of the pressure field at twelve body lengths from three slender delta wings six inches in length. These wings had varying camber and lengthwise lift distributions. The measurements were made in the plane of symmetry of the wing at a Mach number of 1.80 and a Reynolds number of 4.25 x 10^7 per foot at several angles of attack.

Whitham's general formula (see capsule summary G-3) was used in conjunction with the appropriate F-function for the wing, as derived by Walkden (see capsule summary G-6) to compute the theoretical overpressure at any point in the field.

The results of the investigation showed that theory agreed well with measurements of the complete pressure signature for an uncambered model at zero lift. Good agreement was found between the measured maximum overpressures of two models, both having a linear lengthwise distribution of lift coefficient but different attachment lift coefficients. The measured shock strengths of both also agreed well with theory, although the predicted variation of strength with lift coefficient was slightly lower than that measured. The effect was, however, relatively small and of the same size as the experimental error. It was also found that agreement between theory and experiment was not as good in the case of a cambered wing having a nonlinear lift distribution. It was hypothesized that this discrepancy could probably be overcome if the lift distribution were accurately known.

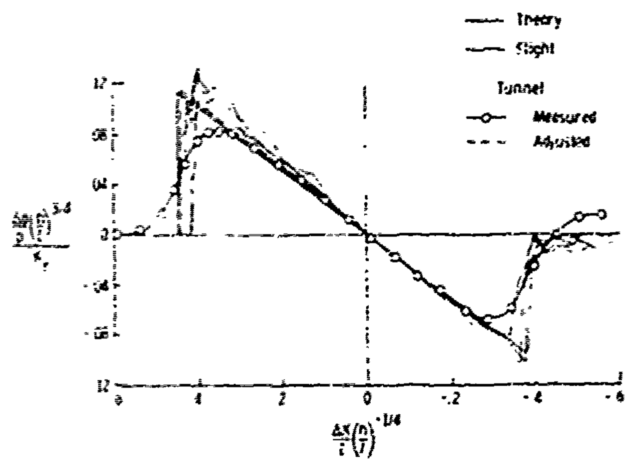
A similar wind tunnel investigation of lift effects was performed by Carlson (see capsule summary G-15). It also confirmed the validity of the theory concerning lift effects on the sonic boom.

This is a well-done investigation with clearly presented data.

G-25
CORRELATION OF SONIC BOOM THEORY WITH WIND TUNNEL AND FLIGHT MEASUREMENTS
Harry W. Carlson
NASA TR R-213, December 1964

This paper uses previously obtained wind tunnel and flight measurements to check the correlation between sonic boom theory and experiment. Improved data reduction methods (see capsule summary G-18) were used to reduce the wind tunnel data, and more precise theoretical estimation techniques were used than were employed in previous work. This involved the use of the reference pressure defined by Friedman, Kane, and Sigalla (see capsule summary P-33), which scaled the signature overpressure to account for atmospheric effects. Previous to this time the normal reference pressure used was the geometric mean of the atmospheric pressure at altitude and that on the ground ($\sqrt{P_a P_g}$). Certain minimization concepts are also discussed, but these are summarized in the "Minimization" section of this report (see capsule summary M-10).

The conclusion that both volume and lift effects contribute to bow shock overpressures was reaffirmed by the results of this review. The results also showed that sonic boom theory (as of 1964) gives reasonably accurate estimates of nominal ground track overpressures for steady supersonic flight in a standard or near standard atmosphere. The agreement between theory, wind tunnel data, and flight measurements for the complete pressure signature was also found to be good, as shown in the figure below, which was taken from this paper.



Comparison of flight, tunnel, and theory pressure signatures

The appendices discuss the author's computer technique for computing bow shock overpressures (see capsule summary G-23) and the adjustment of wind tunnel measurements of bow shock strength to compensate for experimental limitations.

In a previous paper (see capsule summary G-18) Carlson also made a correlation of theory, wind tunnel, and flight measurements. This paper makes use of much more data, however, and is broader in scope.

This reference is a good summary of what had been learned about the generation of sonic booms up to 1964.

G-26
AN EVALUATION OF THE FAR-FIELD OVERPRESSURE INTEGRAL
Raymond M. Hicks and Joel P. Mendoza
Journal of Aircraft, 2 (2), 154-155, March-April 1965

This short note presents the derivation of a method of evaluating the integral in Whitham's asymptotic formula (see capsule summary G-3) that does not involve the use of derivatives. Laplace transforms are used to obtain an expression for the integral of the F-function in terms of the equivalent cross-sectional area due to volume and lift at discrete points along the body. An example calculation is performed for two nonlifting models for which equations for the exact area distributions are known. The calculated overpressures were nearly identical to the exact values calculated using the normal form of the overpressure integral, as shown in the table below.

COMPARISON OF THE MAXIMUM SONIC BOOM OVERPRESSURE PARAMETER WITH THE EXACT SOLUTION.

Configuration 1		Configuration 2	
Exact	Calc.	Exact	Calc.
0.0371	0.0371	0.0687	0.0686

Lansing (see capsule summary G-13) had previously derived an equation for the far-field overpressure integral which avoided the necessity of calculating derivatives of the approximating function (see capsule summary G-15) to the area distribution. However, Lansing used a different mathematical approach and his resulting overpressure equation is also different.

The utility of this method is somewhat restricted because it does not allow the calculation of pressure signatures in detail but only allows for computation of the asymptotic bow shock overpressure.

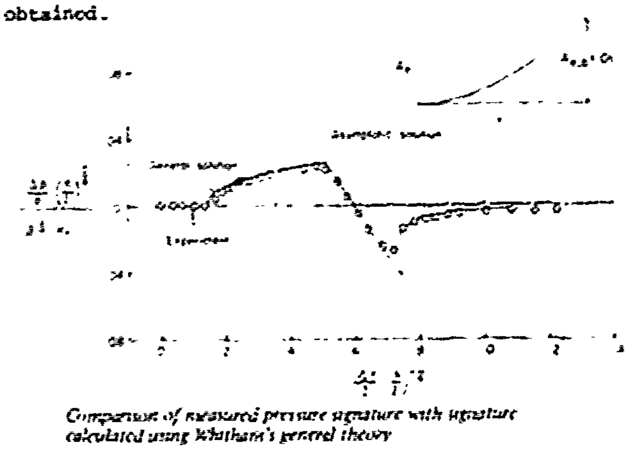
G-27
SOME NONASYMPTOTIC EFFECTS ON THE SONIC BOOM OF LARGE AIRPLANES
F. Edward McLean
NASA TN D-2877, June 1965

This paper presents the results of an investigation into the possible inapplicability of the asymptotic far-field sonic boom theory. In order to determine under what conditions this may occur several equivalent bodies of revolution representing a large airplane at transonic flight conditions were studied both analytically and experimentally.

A nondimensionalized form of Whitham's nonasymptotic formula (see capsule summary G-3) is used to calculate the bow shock overpressure versus altitude for typical large supersonic transports having the equivalent bodies chosen.

The resulting data show that at a Mach number of 1.414 the pressure field of an airplane 230 feet long weighing 450,000 pounds would exhibit nonasymptotic effects at the assumed normal operating altitude of 44,000 feet. Furthermore the asymptotic variation of bow shock overpressure would not begin until from 220,000 to several million feet from the body, depending upon the body characteristics. The results also show that the area distribution of the equivalent body of revolution has a significant influence on the manner in which the bow shock pressure rise parameters approach their respective asymptotes.

In order to experimentally verify Whitham's general (near-field) theory, wind tunnel pressure measurements were made at a Mach number of 1.414 in the flow field of bodies of revolution representing various supersonic transport configurations at an altitude of 4600 feet for an assumed airplane length of 230 feet. The measured pressure signatures are then compared with those calculated from a rigorous application of Whitham's general theory (see capsule summary G-3). The results show that the general theory provides an extremely good representation of the field pressures for all body shapes chosen. The figure below is a typical example of the correlation obtained.



Comparison of measured pressure signature with signature calculated using Whitham's general theory

Previous investigations by Cook (see capsule summary G-24) and Smith (see capsule summary G-12) also demonstrated the validity of Whitham's near-field theory. The agreement of the measured and calculated pressures was not quite as good in these papers as that found by McLean, however.

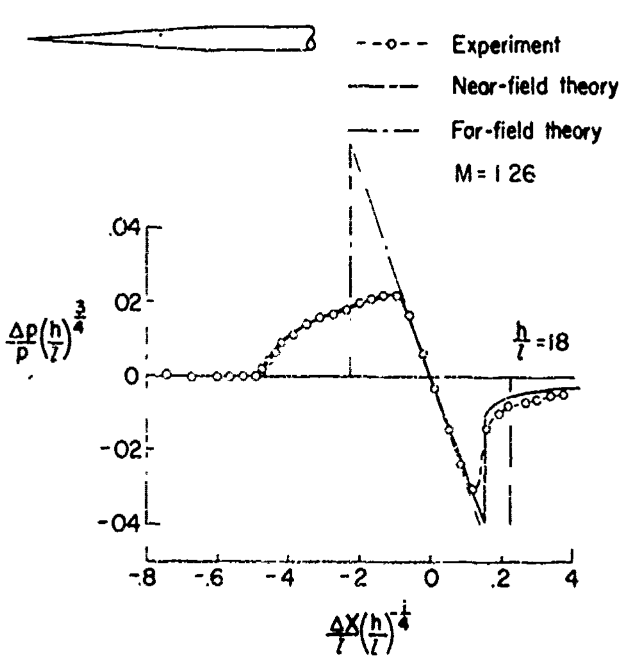
This paper was the first to suggest that far-field theory may not be valid, even for flight at high altitudes.

G-28

A WIND TUNNEL INVESTIGATION OF THE EFFECT OF BODY SHAPE ON SONIC BOOM PRESSURE DISTRIBUTIONS
Harry W. Carlson, Robert J. Mack, and Odell A. Morris
NASA TN D-3106, November 1965

Pressure signature measurements were made at distances of up to 20 body lengths from eight slender bodies of revolution at Mach numbers of 1.26, 1.41, and 2.01. The measured signatures were then compared with those calculated using Whitham's general formula (see capsule summary G-3). Minimization concepts are also discussed.

The results showed that the measured signatures were in good agreement with Whitham's general theory and that values of maximum-overpressure parameter are often much lower than estimates based on the far-field asymptotic formula. Typical comparisons are shown below. These results are the same as McLean's results (see capsule summary G-27). It was also found that near-field theory and experiment were in reasonably good agreement for a blunt-nosed body for which application of Whitham's slender body theory would appear to be questionable. This result is in agreement with the earlier findings of Kane (see capsule summary G-14).



Comparison of measured signature and Whitham's general theory

This paper further demonstrated the importance of near-field effects and the importance of using near-field theory when the asymptotic far-field theory is inapplicable.

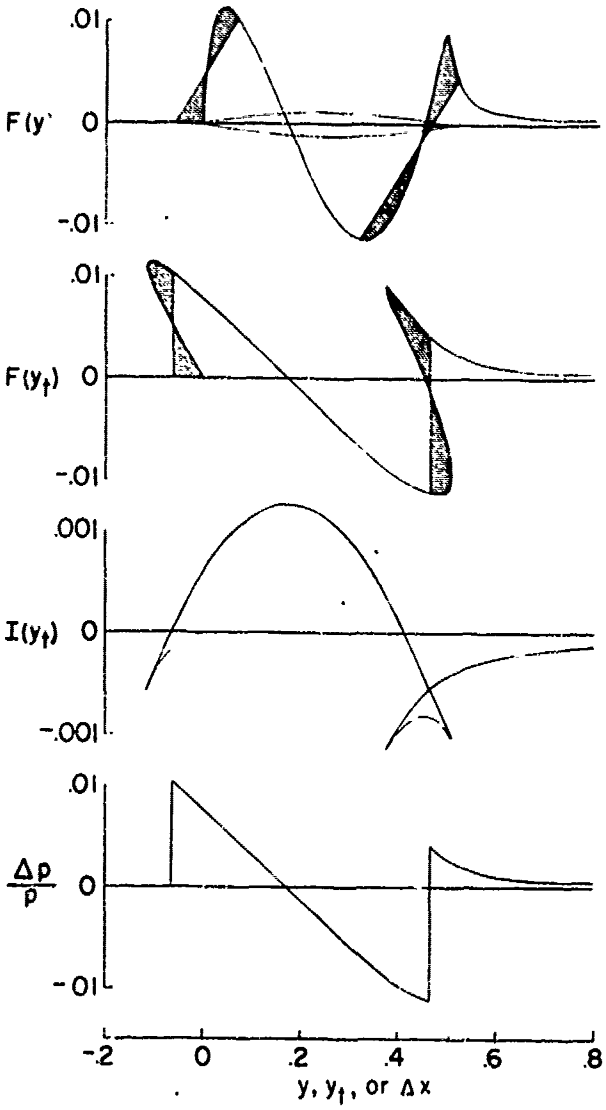
G-29

A NUMERICAL METHOD FOR CALCULATING NEAR FIELD SONIC BOOM PRESSURE SIGNATURES
Wilbur D. Middleton and Harry W. Carlson
NASA TN D-3082, November 1965

A numerical method is given for calculating near-field pressure signatures from Whitham's F(y)-function. The solution is suitable for use on digital computers.

The method presented here is based upon a transposition of the F(y) function to a tilted F(y) or $F(y_t)$, where $y_t = y - k\sqrt{r}\,F(y)$. Replacing y by y_t corresponds to replacing the linear characteristic by the corrected characteristic of Whitham's theory (see capsule summary G-3). Pressure disturbances are propagated along the characteristics, and the magnitude of these disturbances is directly related to the F(y)-function through Whitham's general formula (see capsule summary G-3). The transformation results in a picture of the location of each pressure perturbation in the flow-field at the distance r (for a definition of the nomenclature used here see capsule summary G-3).

The shocks are located from the $F(y_t)$ curve using a numerical version of Whitham's "area-balancing" technique (see capsule summary G-3). This involves dividing the $F(y_t)$ curve into left- and right-running branches and progressively integrating to find the area under these curves. This running integral is called $I(y_t)$. This is equivalent to planimetering the area confined within the boundary of the $F(y_t)$ curve and the line $F(y_t) = 0$. Numerically, this is done by considering all of the left-running lines to contain negative area between the curve boundary and the line $F(y_t) = 0$ and taking the corresponding area for the right-running curves to be positive. The most negative value of y_t for which $I(y_t) = 0$ corresponds to the location of the vertical line which cuts off equal areas of the first tilted lobe. This is the bow shock location. Successive shocks are located at appropriate crossover points of the right-running branches of the $I(y_t)$ curve, where the values of $I(y_t)$ are equal. All of the necessary steps can be performed in a straightforward manner on a digital computer. The figure below, which was taken from this paper, illustrates the basic steps of this technique.



Method for determining near-field signature

Numerical methods had been given previous to this one for computing far-field pressure signatures (see capsule summaries G-13 and G-23, for example). Calculating the near field signature was a more difficult task, however, due to its greater complexity. As a result, this method proved to be a valuable addition to sonic boom prediction techniques. For example, this is the method used by Hayes in NASA CR-1299 (see capsule summary (P-98) for computing the signatures.

G-30
WIND TUNNEL INVESTIGATION OF SONIC BOOM CHARACTERISTICS OF A DELTA-WING-BODY COMBINATION AT MACH NUMBERS OF 1.41 AND 2.01
Odell A. Morris
NASA TN D-3455, June 1966

The purpose of this investigation was to determine whether or not the large lift interference effects produced by a wedge-shaped body mounted on a thin delta wing could be evaluated theoretically to obtain reasonable estimates of the sonic boom overpressures. To accomplish this a delta-wing-body model was tested in the Langley 4x4 foot supersonic wind tunnel at Mach numbers of 1.41 and 2.01.

Whitham's asymptotic formula (see capsule summary G-3) was used to compute the theoretical bow shock overpressure. The predicted overpressures were in close agreement with those measured for all configurations and Mach numbers tested.

The close agreement between calculated and measured overpressures demonstrated that the existing theory was adequate for estimating the influence of large body interference on the bow shock overpressure.

In an earlier investigation Maglieri (see capsule summary G-20) used flight measurements to demonstrate the accuracy of sonic boom theory in predicting the manner in which lift and volume effects combine in the generation of shock waves. This paper deals more specifically with the interference between volume and lift.

This is a very concise, well-written paper.

G-31
APPLICATION OF RICHARDSON'S EXTRAPOLATION TO NUMERICAL EVALUATION OF SONIC-BOOM INTEGRALS
William B. Igoe
NASA TN D-3806, March 1967

This paper presents a numerical method of evaluating the integrals in Whitham's nonasymptotic and general formulas for the sonic boom overpressure. The method is well suited for use with Richardson's extrapolation. The application of Richardson's extrapolation as a method of improving the accuracy of the sonic boom integrals is then demonstrated.

The method deals with the evaluation of F(x) and I(x), where

$$F(x) = \frac{1}{2\pi}\int_0^x \frac{A''(\zeta)}{\sqrt{x-\zeta}}\, d\zeta \text{ and } I(x) = \int_0^x F(\zeta)\, d\zeta .$$

Here A(x) is the effective cross-sectional area of the equivalent body which combines the effects of volume and lift, nondimensionalized with respect to the square of the equivalent body length. F(x) is the Whitham F-function, and X and ζ are the longitudinal distance from the nose along the equivalent body axis nondimensionalized with respect to equivalent body length. The second derivatives of the effective area distribution are approximated by using the three-point formula of the standard central difference technique, which is equivalent to taking the second derivative of a parabolic arc which is passed through three adjacent points. A check of the A"(x) approximation is then obtained by integrating twice to obtain $A(x)_{check}$. The second deviatives are then used to obtain expressions for F(x) and I(x) in terms of h, the width of the interval in X between regularly spaced body stations. This is a form which is suitable for

an error analysis. The dependence of the solution error on the interval spacing, h, is analyzed and only the lowest order terms are retained. A solution with increased accuracy is then obtained by using Richardson's extrapolation to determine the solution which would result from an interval spacing of zero. Finally, some numerical examples are presented to show a possible application of the extrapolation technique.

The numerical procedure for evaluation of F(x) and I(x) used in this paper is essentially the same as Carlson's (see capsule summary G-23), the main difference being in the method by which the derivatives of the equivalent body effective area distribution are obtained. The standard central difference formulas were used for this step in this paper because it appeared most readily amenable to an error analysis and to the subsequent application of Richardson's extrapolation. In addition to Carlson's, several other numerical methods for use in sonic boom theory were available at the time this report was published (see capsule summaries G-13, G-12, and G-22, for example).

This method is suitable only for smooth bodies and is somewhat cumbersome. Direct application of the Stieltje's integral (see section 2.3 of Volume I of the Sonic Boom Literature Survey) eliminates the necessity of deriving the second derivative, which is what causes all the problems.

G-32

A NEAR-FIELD APPROACH TO THE SONIC BOOM PROBLEM
F. A. Woodward
NASA CR-73109 (Boeing Document No. D6-15046)
August 1967

This paper presents the results of an investigation into the feasibility of applying a wing-body analysis method which differs from Whitham's to the problem of calculating the pressure signature in the near field. In this method the configuration is represented by a spatial distribution of singularities located in the plane of the wing and along the body axis. This was done with the hope that an improved theory in the near field may give additional understanding of the wave interaction problem, which in turn could lead to new techniques for modifying or reducing the pressure signatures in the far field.

Using the method described above, two different expressions for the characteristics are developed in terms of the singularity strengths and perturbation velocities. One expression is for low Mach numbers and the other is for high Mach numbers. The shock locations are then determined by placing them at the intersection of the characteristics in such a manner that the angle of intersection is bisected - the same method that Whitham used. The shock locations for a 10° and a 15° half-angle cone are then determined using both this method and Whitham's method and the results are compared with the "exact" shock location determined from shock tables. The results show that Whitham's formula is definitely inferior for 15° cones at all Mach numbers, and for 10° cones above $M_\infty = 2.0$. This is not a surprising result, since Whitham's method in the near-field applies only to slender, pointed bodies at low Mach numbers, while no such assumptions were made in deriving the method used in this paper.

It was concluded by Hicks, Mendoza, and Hunton that Whitham's theory is not valid above Mach 3 (see capsule summary G-33). In view of this and in view of the fact that Whitham's theory applies only to slender bodies, it appears that the method outlined in this paper might serve as a useful complement to Whitham's theory for nonslender axisymmetric bodies. But the method described here is not valid for use with three-dimensional flows, since no correction of the azimuthal position of the characteristics is made.

G-33

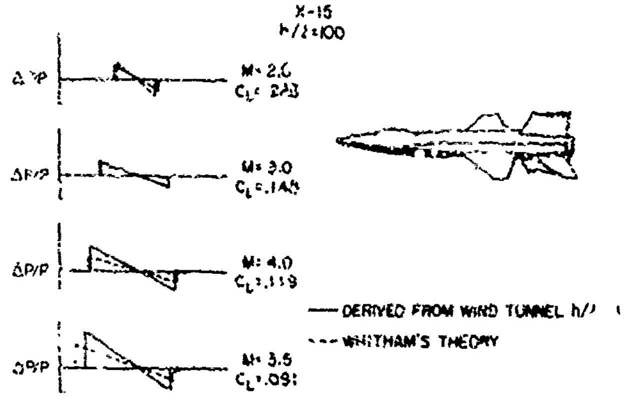
SOME EFFECTS OF MACH NUMBER AND GEOMETRY ON SONIC BOOM
Raymond M. Hicks, Joel P. Mendoza, and Lynn W. Hunton
NASA TN D-4214, October 1967.

The results of an investigation into the validity of Whitham's theory at hypersonic Mach numbers is presented. The effect of changing the geometry of hypersonic configurations on the sonic boom level is also investigated.

Five models were tested in the Ames 9- by 7-Foot and 8- by 7-Foot Wind Tunnels at Mach numbers of 2 and 3 respectively and at Mach numbers of 4 and 5.5 in the 21-Inch Hypersonic Wind Tunnel of the Jet Propulsion Laboratory. The models were a 7.5° half-angle cone cylinder, a model of the X-15 airplane, and three hypersonic transport models: a blended-wing-body, a delta-wing-body, and an all body configuration.

The comparison between experiment and theory was made for an altitude of 100 body lengths. Since it was not practical to obtain wind-tunnel data at this distance from the model, an experimental technique developed at Ames for deriving sonic boom characteristics from near field data for any greater altitude was used. This consists of determining the F-function from a near field pressure signature measured in the wind tunnel. Once the F-function is known the pressure signature at any higher altitude can be calculated by using Whitham's theory. For a description of this extrapolation technique, see capsule summary G-34.

A comparison of wind tunnel data with Whitham's theory showed that the correlation is fairly good at Mach numbers of 2 and 3 but theory deviates rapidly from experiment above Mach 3. Theory underpredicts the strength of the bow shock at Mach numbers of 4 and 5.5, while it overpredicts the experimental shock angle at high Mach numbers. The figure below, taken from this paper, illustrates the Mach number effect.



Mach number effect

Earlier investigations had confirmed the validity of sonic boom theory in predicting both lift and volume effects for Mach numbers less than three (see capsule summaries G-15, G-24, G-7, G-9, G-12, G-16, G-20, G-23, G-18, G-25, and G-30). This investigation defined the limits of Whitham's theory, as far as Mach number is concerned.

This is a very clear, concise report with well-chosen figures.

G-34
PREDICTION OF AIRCRAFT SONIC BOOM CHARACTERISTICS FROM EXPERIMENTAL NEAR-FIELD RESULTS
Raymond M. Hicks and Joel P. Mendoza
NASA TM X-1477, November 1967

This paper presents the results of a study conducted to determine the extent to which measured near-field pressure signature data can be used for predicting the general overpressure characteristics of a given configuration. The motivation for this method was the difficulty in calculating an accurate theoretical lift contribution to the airplane equivalent area distribution.

The method used is a straightforward application of Whitham's theory in the near-field. The pressure signature is measured in the wind tunnel a short distance from the model and the F-function of the model is determined from this signature using the following two equations:

$$F(y) = \frac{\sqrt{2\beta r_1}}{\gamma M^2}\frac{\Delta P(y)}{P};\quad y = x - \beta r_1 + k r_1^{1/2} F(y)$$

where

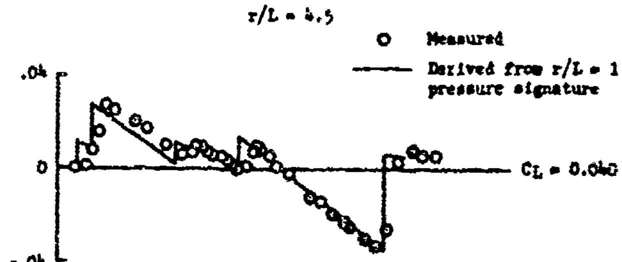
$\beta = \sqrt{M^2-1}$
P = undisturbed reference pressure
$\Delta P(y)$ = sonic boom overpressure at y-location
r_1 = altitude

$$k = \frac{(\gamma + 1)\ M^4}{\sqrt{2}\,\beta^{3/2}}$$

y = distance along longitudinal axis of aircraft measured from the nose

This experimentally determined F-function can then be used to determine the pressure signature at any distance ratio greater than that used for the original measurement by a direct application of Whitham's method (see capsule summary G-3).

To check the validity of this technique a 12-inch model of the XB-70 airplane was tested in the Ames 9- by 7-Foot Wind Tunnel at a Mach number of 1.8 and at distance ratios, r/ℓ, of 1.0 and 4.5 (ℓ = length of airplane, r = distance from airplane). The pressure signature obtained at a distance ratio of 1.0 was used to predict pressure signatures at distance ratios of 4.5 and 290. The latter distance ratio corresponded to available flight data for the XB-70. The results (see figure below) showed good correlation between the derived pressure signature and the wind tunnel measured signature at a distance ratio of 4.5 and between the derived signature and the flight measured signature at r/ℓ = 290 (except for a slight discrepancy in the location of the tail shock, which was thought to be due to a sting support which was too short, and to the failure of the model to simulate the flow of hot gases from the engines).



Comparison between derived pressure signature and wind tunnel signature

The utility of this method is demonstrated in another investigation performed by Hicks, Mendoza, and Hunton (see capsule summary G-33), where it is used in conjunction with a wind tunnel study to determine the Mach number limitations of Whitham's theory.

The significance of this testing technique lies in the fact that it generally permits the study of larger, more accurate models and smaller distance ratios which result in increased pressure levels and, therefore, better definition of the pressure signature. Furthermore, use of this technique permits accurate sonic boom predictions to be made without the calculation of an accurate theoretical lift distribution and interference effects. These both present some limitations due to real flow effects such as local boundary layer separations.

G-35
EXPERIMENTAL AND ANALYTICAL RESEARCH ON SONIC BOOM GENERATION AT NASA
Harry W. Carlson
NASA SP-147, Sonic Boom Research, 1967, pp 9-23

This is a summary of sonic boom research by the NASA during the period from 1958 to 1967. Sonic boom generation theory is reviewed, and several examples of wind-tunnel and flight test verifications of the theory are given. It is concluded that the most important contributions made by NASA research during this period are as follows:

(1) The Whitham-Walkden-Hayes theory was verified in wind tunnel tests of simple wings and bodies.
(2) The theory was extended to cover real airplane shapes by the development of numerical methods programmed for use on high-speed digital computers.
(3) The sonic boom program and related programs were made available to the airframe industry and were in widespread use.
(4) The general applicability of the prediction methods to airplane steady level flight were shown to be in correlation with tunnel and flight-test data.
(5) Minimization concepts were developed and verified in wind-tunnel tests.

Earlier Carlson had given a good summary of the state of the art of sonic boom generation theory as of 1964 (see capsule summary G-25). This paper served the same purpose for 1967.

G-36
AN ESTIMATE OF THE SUPERSONIC FLOW FIELD ABOUT AN AXISYMMETRIC BODY WITH AN N-WAVE PRESSURE TRACE
Roger W. Luidens
NASA TN D-4935, December 1968

An analysis of the flow field about an axisymmetric body at zero angle of attack which produces an N-wave pressure trace is presented. The purpose is to develop closed form relations for estimating the maximum overpressure and length of the pressure signature.

The analysis differs from Whitham's approach in that the assumption of nonisentropic flow is made from the beginning. The analysis is then made based on the conservation equations of mass, momentum, and energy, rather than Friedrichs' hypothesis, that of patching separate isentropic solutions by interposed shocks. This method shows how the entropy increase in the flow field shock waves contributes to the attenuation of the shock wave initial static pressure rise with increasing distance from the body. This effect occurs implicitly in Whitham's far field analysis, which is based upon Friedrichs' hypothesis.

Results calculated from the derived closed form expressions for the maximum overpressure and the length of the positive lobe of the pressure signature are compared with data obtained from a previous wind tunnel study (see capsule summary G-28). The agreement is found to be fairly good, indicating that this may be a convenient method for estimation purposes. This work is directed mainly toward improving on Whitham. As a result it better estimates results for nonslender bodies and higher Mach numbers where the isentropic assumption breaks down. However, Whitham's theory is more than adequate for most engineering applications.

G-37
THE GENERATION OF SHOCK WAVES BY SUPERSONIC PROJECTILES
Harry L. Runyan
Presented at Short Course on Generation and Propagation of Shock Waves With Application to Sonic Boom, The University of Tennessee Space Institute, Tullahoma, Tennessee, December 12, 1968

This paper presents a description of Whitham's theory. It is a well-written paper that is very clear in its explanations of the derivation and concepts of this theory. For a discussion of Whitham's theory the reader is referred to capsule summary G-3.

G-38
FAR-FIELD SONIC BOOM WAVEFORMS
R. Seebass and F. Edward McLean
AIAA Journal, June 1968, pp. 1153-1155

A correction to Whitham's far-field (asymptotic) waveform is presented in this note. The correction involves the relocation of the rear shock to compensate for the tail pressure wave when the ultimate equivalent body radius is nonzero (which is the case whenever there is lift acting on the body). Whitham did not make this correction in his original theory (see capsule summary G-3). The inclusion of this correction was found to be necessary in order to properly account for the transfer of the airplane weight to the ground. The additional term is proportional to $r^{1/8}$.

The correct first order results for the location of the front and rear shock waves, the pressure behind the front shock, the linear decrease with X to its value ahead of the rear shock wave, and the pressure in the tail wave behind the rear shock are given in this paper. The NASA Langley computer program, which is based upon the near-field method developed by Middleton and Carlson, was used to determine the pressure signature below an XB-70 airplane. This result is compared with the corrected and uncorrected far-field waveforms. The corrected waveform shows much better agreement with the computed waveform in the region of the rear shock than Whitham's classical far-field waveform.

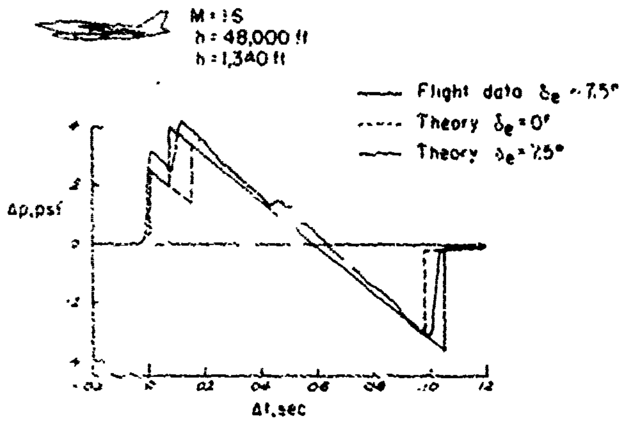
In an earlier paper (see capsule summary G-17) Sigalla used the full linear theory to demonstrate the transfer of weight from a lifting body to the ground. On the basis of his study he concluded that the front lobe of the asymptotic far-field waveform must be larger than the rear lobe, including the tail pressure wave. The present paper demonstrates that this is the case and shows how the size of the rear lobe must be adjusted to compensate for the tail pressure wave.

G-39
LABORATORY SONIC BOOM RESEARCH AND PREDICTION TECHNIQUES
Harry W. Carlson
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 29-36

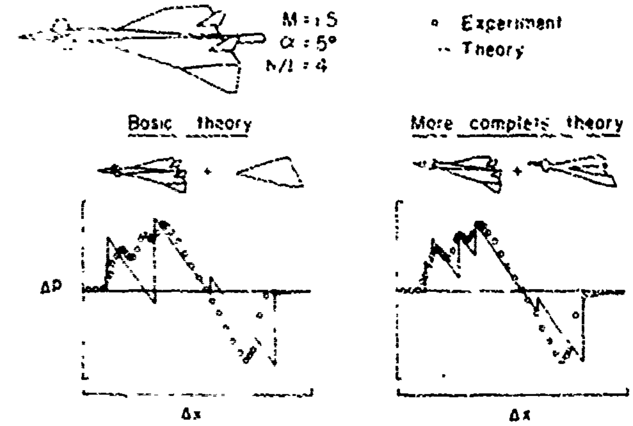
This report is an update of the paper presented by Carlson at the previous NASA sonic boom conference (see capsule summary G-35). It considers the refinement of prediction techniques discussed in the previous paper, and the extension of wind-tunnel tests into the low hypersonic speed range.

It is shown that a more complete theoretical treatment which considers the angle of attack attitude in area and lift developments, and which accounts for interference effects by employment of a warped lifting surface in conjunction with a canard results in an improved correlation between theory and wind-tunnel measured signatures in the extreme near field

of a complex airplane model. It is also shown that taking into account control surface deflections is of value whenever high precision is required in theoretical predictions. These findings are illustrated in the two figures below.



Improvement due to consideration of control surface deflection



Improvement of theory due to use of warped lifting surface

The preliminary low hypersonic wind tunnel tests discussed indicate that the validity of Whitham's theory decreases above Mach 3. An in-depth discussion of these measurements can be found in the paper summarized in capsule summary G-54.

This is a good summary of the advancements made in sonic boom theory between 1967 and 1968.

G-40
CURRENT RESEARCH IN SONIC BOOM
Lynn W. Hunton
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 57-66

This paper reviews the research conducted on the sonic boom at the NASA Ames Research Center during the 1967-68 time period. This included the development of a new near-field experimental data method, a study of the effects of Mach number to 5.5, and a boom minimization study.

The near-field extrapolation technique discussed here uses a measured near-field pressure signature to determine the F-function of the model. This F-function can then be used in conjunction with Whitham's theory to find the pressure signature at any greater distance. This technique is discussed fully in the paper summarized in capsule summary G-34.

The high Mach number study showed that the validity of Whitham's theory decreases above Mach 3.0. For further details of this study see capsule summary G-33.

The minimization study is summarized in capsule summary M-31.

This paper is a good brief summary of the results of several investigations discussed in depth elsewhere.

G-41
NONLINEAR EFFECTS ON SONIC BOOM INTENSITY
M. T. Landahl, I. L. Ryhming, and L. Hilding
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp 117-124

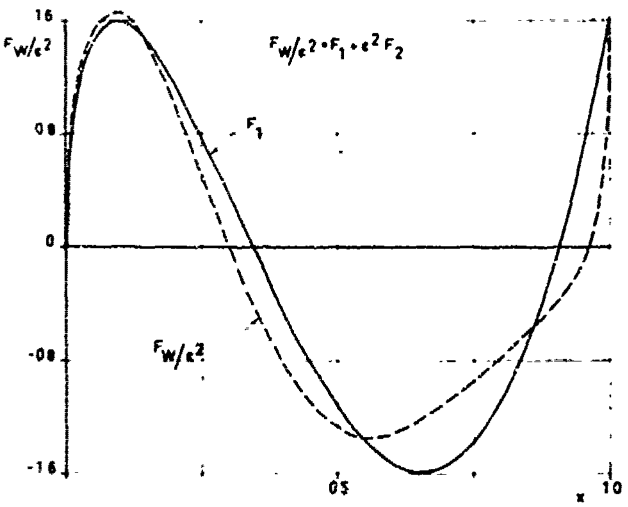
The method of matched asymptotic expansions is used in this paper to assess the importance of second-order effects on the flow field in some simple cases. The method consists of expanding the perturbation velocity in the far field in terms of ϵ, a thickness parameter of the body, inserting the expansion into the partial differential equation for the velocity potential and equating terms of like power in ϵ. The resulting equations are solved to get parametric far-field solutions for the perturbation velocity and the characteristics. The solution is then completed by matching the first- and second-order far field solutions with the first- and second-order inner solutions, respectively. The cases studied are two-dimensional flow, axisymmetric flow, over a slender body and three-dimensional non-axisymmetric flow.

For two-dimensional flow the expressions for the perturbation velocity and the characteristics are derived to second order in terms of the Mach number and airfoil characteristics. For axisymmetric flow over a slender body, the same quantities are derived in terms of the Mach number and a second order F-function. This second order F-function is defined in terms of the second order source strength distribution. For nonaxisymmetric three-dimensional flow no second order near-field solution was readily available; hence, the second-order correction to the F-function could not be calculated for this case.

It was found in the analysis that for three-dimensional flow the first-order equation describes the far-field wave structure very accurately with a relative error of only $O(\epsilon^4)$. As a consequence the dominating higher order effect is that attributed to the nonlinear relationship between body slope and

disturbance velocities at the outer boundary of the near-field, which produces a second order correction to the F-function.

An example calculation is made of the first- and second-order source strengths and F-functions for a parabolic body of revolution of thickness ratio G = 0.07. The results show that the second-order effects are fairly small near the forward portion of the body but quite noticeable toward the rear. This indicates that the higher order effects would have most influence on the rear shock. Also, the correction term increases in magnitude with the Mach number, so that it becomes more important at high supersonic speeds. The figure below gives a comparison of calculated first and second order F-functions.



Comparison of first and second order F-functions

In a later paper (see capsule summary G-62), Landahl, Ryhming, Sorenson, and Drougge make use of the findings of this paper to derive a new method of determining sonic boom strength from near-field measurements. In this method, instead of measuring a pressure distribution, the streamline inclination angles at the edge of the near flow field are measured along lines of constant distance from the model at different azimuthal locations.

In spite of its limited scope, this paper does indicate for which regions of the flow nonlinear effects will be important. The treatment of this subject is continued in a later paper by Landahl, Ryhming, and Lofgren (see capsule summary G-61).

G-42
PRELIMINARY INVESTIGATION OF FLOW FIELD ANALYSIS ON DIGITAL COMPUTERS WITH GRAPHIC DISPLAY
Harvard Lomax
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 67-71

Results are presented of a preliminary investigation into the development of methods for numerical calculation of the flow about airplanes moving at supersonic speeds by reducing the basic partial differential equations to difference equations which are programed for a digital computer. The principal difficulty of this scheme lies in the fact that it implies a continuity in the dependent variables that does not exist for the initial and boundary values that are pertinent. A cathode ray tube connected directly to the high speed core of the computer allows use to be made of the visual display in an attempt to isolate the shocks from the continuous portions of the flow and calculate both by their individually appropriate techniques. This opens the possibility of devising new, or reviving parts of old, numerical techniques. In exploring these possibilities, preliminary studies indicated the following.

(1) Differencing schemes for hyperbolic partial differential equations governing discontinuous functions are good when they approach spacings that are equivalent to the method of characteristics, and this property is not necessarily connected to their stability.
(2) Artificial stabilizing methods based on continuous functions not only force errors to decay, but also can force the entire solution to (artificially) decay. Such methods do not appear appropriate for problems involving the sonic boom.

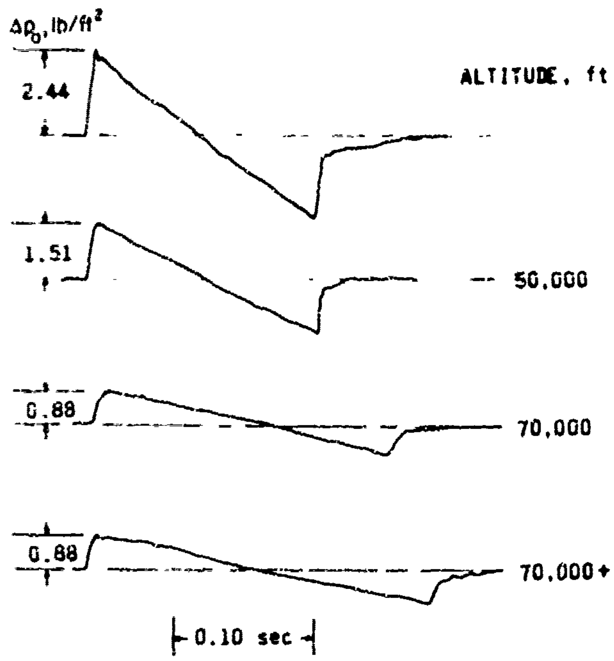
Results obtained using the method described here are discussed in a later paper by Lomax and Kutler (see capsule summary G-63).

G-43
SONIC BOOM GROUND PRESSURE MEASUREMENTS FOR FLIGHTS AT ALTITUDES IN EXCESS OF 70,000 FEET AND AT MACH NUMBERS UP TO 3.0
Domenic J. Maglieri
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 19-27

This paper presents the results of an investigation into the effects of extreme altitude on the sonic boom generated by a large airplane. The data were obtained from 35 flights of the SR-71 vehicle at altitudes in excess of 70,000 feet and at Mach numbers to 3.0.

The data showed that for flights above 70,000 feet the bow shock overpressure was in the neighborhood of 0.9 psf. The data also suggested that the increased altitude results generally in longer rise times (see figure below). No unusual phenomena were encountered for the extreme altitude and Mach number ranges of these tests, and the results fit generally into the established patterns of other available sonic boom flight data from F-104, B-58, and XB-70 aircraft. Several results concerning propagation are also discussed, but these are summarized in capsule summary P-92.

This paper contains some of the first measurements of pressure signatures produced by airplanes flying at such high Mach numbers.



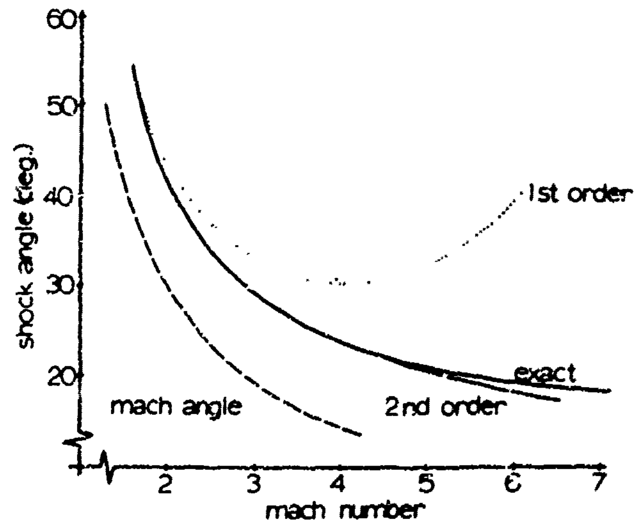
SR-71 pressure signatures

G-44
SECOND-ORDER WAVE STRUCTURE IN SUPERSONIC FLOWS
David A. Caughey
NASA CR-1436, September 1969

This paper presents a second-order perturbation theory for bodies in uniform supersonic flight in an inviscid fluid. Particular emphasis is placed upon the behavior of the wave systems at large distances from the body. The method of matched asymptotic expansions is used, which involves matching the solution at large distances to a local solution near the body which satisfies the actual boundary conditions.

The essential (or cumulative) nonlinearities in the solution at large distances from the body are accounted for by rescaling the independent variables of the problem in such a way as to bring these nonlinearities into the linear problem. The resulting first order equation is nonlinear, but solvable. The higher order equations are again linear.

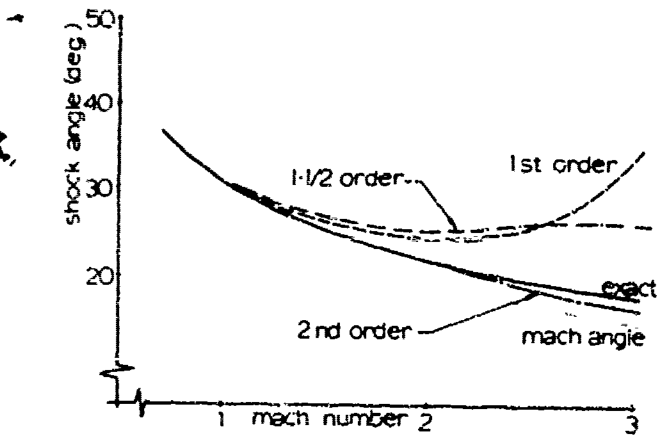
For planar flows, the solution valid at large distances from the body (referred to in this paper as the wave structure solution) is uniformly valid to the body surface, and the boundary conditions are applied directly. The simple wave results of Friedrichs as corrected and extended by Lighthill ("General Theory of High Speed Aerodynamics," Section E, Princeton, 1954) are confirmed for this case, with a minor correction noted for the location of the rear shock at very great distances from the body. The theory does not provide a second-order check on global integrals giving lift and drag and the positions of the trailing shocks unless account is taken of local third order effects behind the trailing shocks. The figure below shows the improvement afforded for the front shock by inclusion of second order effects for the flow over a slender wedge. It can be seen that for Mach numbers greater than 2, second order theory gives a significant improvement over first-order theory.



Shock angle on twelve-degree wedge

For flows about finite bodies, the wave structure (large distance) solution must be matched with a quasi-cylindrical, local solution to provide the inner boundary condition. The lack of local second order solutions of any generality results in a limitation of the types of bodies for which full second order solutions can be obtained. A reasonably complete second-order theory exists only for flows over a body of revolution. The matching of the inner and outer solutions is considered in detail for these flows. The nature of problems encountered for flows about non-axisymmetric and planar bodies is discussed briefly.

It is shown that the local second order solution determines only a one-and-one-half order solution in the wave structure region. Thus, even though the complete general solution is derived for the second-order equation, the local third-order solution is required to effect the matching which determines the inner boundary condition, and such solutions can be obtained for only the simplest conical geometries. Numerical results from the calculation of the shock position in a conical flow, as shown in the figure below, indicate that the one-and-one-half order solution does not give results that are appreciably better than the first order theory. It is necessary to go to the full second order theory, which is based upon the local third order theory, to achieve noticeable improvement.



Shock angle on ten degree cone

Landahl, Ryhming, and Hilding performed a similar, though less extensive investigation which dealt with second order effects for planar flows, axisymmetric flows, and three-dimensional flows. They independently noted the need for an intermediate homogeneous wave structure solution (which is termed the one-and-one-half order solution in the present paper), which is determined by the local second order solution. See capsule summary G-41 for details of this study.

This study is significant for two reasons. First it can provide increased numerical accuracy for solutions simple enough to be calculated analytically. Secondly, the study of the second order solution verifies the uniform validity of the first order (Whitham's) solution, gives greater insight into its nature, and provides limits on its accuracy.

G-45

SECOND-ORDER WAVE STRUCTURE: PLANAR FLOWS

David A. Caughey and Wallace D. Hayes

Aerodynamic Noise, Proceedings of AFOSR-UTIAS Symposium, 1969, pp. 423-433

This paper presents the second-order theory for the weakly nonlinear wave system emanating from a body in uniform supersonic flight. This involves finding the second term in an asymptotic series representation of the solution, for the velocity potential, valid to all distances from the body. This is accomplished by the method of matched asymptotic expansions, wherein the solution at large distances from the body is matched to a local solution near the body which satisfies the actual boundary conditions. In the large-distance solution, the cumulative nonlinear effects which render the classical linearized theories useless are taken into account by rescaling the independent variables of the problem in such a way as to bring these nonlinearities into the linear problem. Shocks are inserted according to the "angle property" (see capsule summary G-3). This analysis is limited to planar flows.

The results confirm the results of Friedrichs ("Formation and Decay of Shock Waves," Comm. Appl. Math., 1, 211-245, 1948) as presented and corrected by Lighthill ("General Theory of High Speed Aerodynamics," Section E, Princeton, 1954) for the case of planar flows. This theory, however, presents a method which is easily extended to the case of flows about finite bodies, where the cylindrical nature of the problem precludes the use of Friedrichs' simple wave idea. The extension to finite bodies is made in a later paper by Caughey (see capsule summary G-44). The reader is referred to that paper for a more extensive discussion of the method used here.

G-46

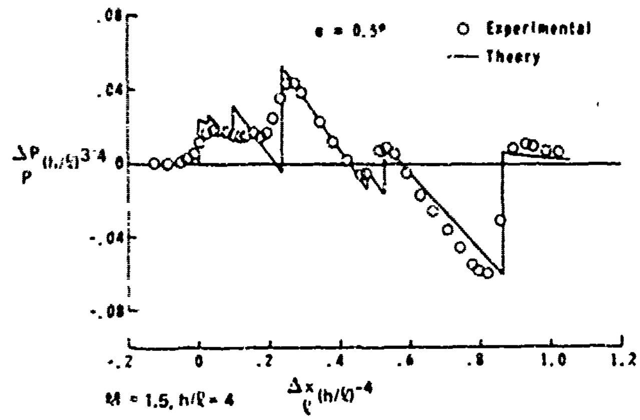
SONIC BOOM CHARACTERISTICS IN THE EXTREME NEAR FIELD OF A COMPLEX AIRPLANE MODEL AT MACH NUMBERS OF 1.5, 1.8, AND 2.5

Odell A. Morris, Hilton Lamb, and Harry W. Carlson

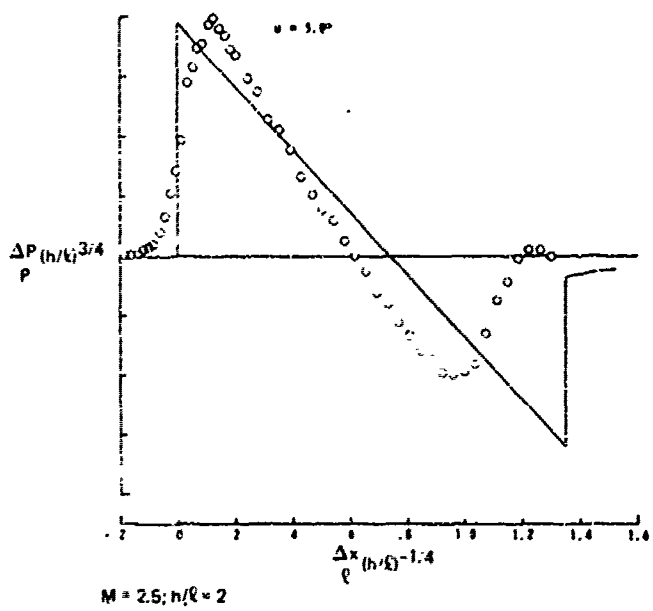
NASA TN D-5755, April 1970

The results of an experimental investigation of the validity of sonic boom theory in the extreme near field are presented.

A 15-cm-long model of an XB-70 bomber was tested in the Langley Unitary Plan Wind Tunnel at Mach numbers of 1.5, 1.8, and 2.5. Pressure signatures were measured at distance-length ratios of 2 and 4 at angles of attack of 0.5°, 2.0°, 3.5°, and 5.0° with various canard and elevon settings. The numerical method developed by Middleton and Carlson (see capsule summary G-29) was used to calculate theoretical near-field pressure signatures, which were then compared with the measured signatures. The results showed good agreement between experiment and theory at $M = 1.5$ for the general signature characteristics. However, as the Mach number was increased, the agreement became poorer with the larger discrepancies occurring in the tail region of the signature at the higher angles of attack. A comparison of the data for the two distances measured ($h/\ell = 2$ and $h/\ell = 4$) showed that there was a general improvement between theory and experiment as the distance was increased. The figures below are examples of the best and poorest correlation obtained.



Comparison of experimental and theoretical pressure signatures



Comparison of experimental and theoretical pressure signatures

In order to check further on the variation of signature with distance, an extrapolation of the experimental data was made for values of h/ℓ from 2 to 64 using the method developed by Hicks and Mendoza (see capsule summary G-34). These extrapolated signatures were then compared with theoretical signatures calculated using Middleton's and Carlson's numerical technique. For h/ℓ = 4, the extrapolated data show good agreement with the measured experimental signature. Further increases in distance from the model showed gradual improvement in the agreement between the extrapolated data so that as the values of h/ℓ approached a distance corresponding to normal flight altitudes (h/ℓ = 64) very good agreement was obtained.

Previous wind-tunnel investigations of sonic boom theory in the near field had been conducted by Cook (see capsule summary G-24), McLean (see capsule summary G-27) and Carlson, Mack, and Morris (see capsule summary G-28). None of these made measurements as close to the body as those made in this investigation, however.

As mentioned by the authors, Whitham had indicated that difficulty might be expected in using his method to predict the signature very near the body. This is one possible explanation for the slight discrepancy noted between experiment and theory for the measurements closest to the body. The high angle of attack agreement is poor probably because at this flight condition the equivalent body is no longer slender. The same is true for the high Mach number data.

G-47
HYPERSONIC BOOM
A. Richard Seebass
Boeing Scientific Research Laboratory, Flight Sciences Laboratory Tech. Comm. 030, June 1970

This paper presents an estimate of the strength of the bow shock wave for a hypersonic vehicle. The shock strength in a homogeneous atmosphere is considered first. This is then corrected for the effects of atmospheric stratification and vehicle flight path angle.

It is assumed that the main contribution to the shock wave strength is due to the vehicle drag. As a result, the strength of the bow wave is independent of azimuthal angle. An expression previously derived by Sakarai for the strength of a blast wave is used as the starting point. But since this is a strong-shock expression it is not applicable far from the vehicle. In order to produce the correct asymptotic variation of ΔP for large r, an ad hoc generalization is made in the equation for the bow shock overpressure. The use of this generalization is justified by showing that it gives results which agree with previously derived experimental data. A final expression is then derived which takes into account flight path angle and density stratification of the atmosphere. The expression given in the paper has an error in it. The correct equation is:

$$\Delta P = 4.2 \left(e^{-h/8H}\right)\left(\frac{H}{h}\right)^{1/2}\left[\frac{n_L W}{L/D} \times 10^{-5}\right]^{3/8}$$

where ΔP = bow shock overpressure
h = altitude
H = atmospheric scale height
W = weight
L = lift
D = drag
n_L = load factor

In a later paper Pan and Sotomayer also derive an expression for the bow shock overpressure of a hypersonic vehicle. Their method involves matching numerical solutions for the strength of cylindrical shock waves to the weak shock expressions given by Whitham (see capsule summary G-3) and is done only for a homogeneous atmosphere.

This paper was the first attempt to extend sonic boom theory into the hypersonic regime.

G-48

APPLICATION OF WHITHAM'S THEORY TO SONIC BOOM IN THE MID- OR NEAR-FIELD

Y. S. Pan

AIAA Journal, 8 (11), November 1970

A modification of Whitham's theory in the near-field of a slender body of revolution is presented. The purpose of this modification is to obtain relations between the flow disturbances and the F-function which are uniformly valid at all points of the flow-field. This, in turn, allows an accurate extrapolation to be made of a known disturbance signature in the near field to the far field. Large models in wind tunnels can then be used to obtain the "known" disturbance.

Since the disturbance of the flow-field due to a slender body is equivalent to that caused by a streamtube enclosing the body in a nearer field, the flow-field over the streamtube is considered instead of the flow-field over the body. The radius of the streamtube is made arbitrary; thus the relations derived are valid at any distance from the body.

Using linearized supersonic theory, the flow disturbances on the streamtube surface are expressed as integrals of the source distribution of this streamtube. These integral equations are then solved to get the source distribution in terms of the disturbances on the streamtube. Since the F-function is defined in terms of the source distribution (see capsule summary G-3), the F-function of the streamtube can then be found in terms of the disturbances, and the disturbances can be found in terms of the F-function. The expression for the streamwise perturbation velocity contains a term not contained in Whitham's corresponding expression. This additional term is due to near-field effects and vanishes at large distances. Thus when this perturbation velocity is used to correct the linear characteristics, an additional term is obtained in the equation for the characteristics which also vanishes at large distances. This additional term modifies the longitudinal location of the characteristics.

Having derived the expression for the "exact" characteristics, the F-function at any distance r from the body may be found from a known F-function at $R (R < r)$, where R is the radius of the streamtube upstream of the body. This is due to the fact that the value of F is constant along the characteristics. The F-function at R can be determined from a measured pressure signature.

In another paper (see capsule summary G-50) Pan performs a similar derivation for an arbitrary three-dimensional body, as contrasted to the present derivation, which was limited to bodies of revolution.

The significance of this paper is that it provides a method of extrapolating a measured F-function of a slender body of revolution that is valid for the entire flow-field, even for points in the extreme near-field.

G-49

THE INFLUENCE OF NEAR-FIELD FLOW ON THE SONIC BOOM

K. Oswatitsch and Y. C. Sun

ICAS Paper No. 70-20, 1970

The purpose of this paper is to check the validity of equivalence of a lifting wing to an axisymmetrical body and the accuracy of Whitham's asymptotic far-field theory. This is done using the analytical method of characteristics to investigate the problem of an incident triangular plate with supersonic leading edges and constant loading. The essential features of the method consist of the introduction of a coordinate system composed of characteristic surfaces and in the expansion of space variables and physical flow quantities in an ascending power series of some small parameters (such as angle of incidence, wing thickness, etc.) in this coordinate system of characteristics. Only the first order approximation is used. Whitham's theory is closely related to the first approximation of this theory, except that the simplifying large distance assumptions made by Whitham are not made here. This allows an assessment of the influence of near-field flow. The angle property (see capsule summary G-3) is used to locate the front shock of the wing, to which this study is limited.

The flow-field of the wing is divided into four radial regions. These are:

1. The region of conical flow which is not influenced by the trailing edge.
2. The region in which the flow is characterized by the expansion from the sharp trailing edge of the wing. This region has features of plane flow.
3. An intermediate region which is influenced by the trailing edge but not by the wing tips.
4. The region influenced by the whole wing.

An estimate is made of the relative extent of the various regions of the flow for several typical wing configurations and flight conditions. This estimate shows that, if regions 1 and 2 are considered to be near-field regions, then in many cases only near-field flows will be involved in the study of sonic boom due to the front shock.

The method of vortex distribution is then used to derive expressions for the perturbation velocities, shock location, and shock strength in regions 1 and 2 in terms of the vortex distribution on the wing.

There are three principal conclusions reached as a result of this study. These are:

1. In the plane of symmetry vertical to the wing, the equivalence of the wing to a body of revolution exists in region 1 under the assumption of $\bar{\sigma}^2 C_L << 1$, where C_L = lift coefficient, $\bar{\sigma} = \tan\omega \tan\alpha_\infty$, ω = complement of sweep angle, and α_∞ = free stream Mach number. However, in planes normal to wave fronts arising

from the leading edges, flows with the nature of plane waves will prevail in the near field, and no equivalence to an axisymmetrical body will apply there. In region 2, flow with the nature of a plane flow will affect a wide intermediate field of flow until the strong disturbances of plane-wave nature are finally attenuated in the far field. In this intermediate field of flow, the wing can again not be replaced by an equivalent body of revolution.

2. Whitham's asymptotic far-field theory is valid on the condition that $\tan\omega\ (\zeta/\eta)^{1/2} \ll 1$ applies on the shock, where ζ and η are the characteristic coordinates defined by $\zeta = x_o - y_o$ and $\eta = x_o + y_o$ and x_o and y_o are the first terms in the expansion of the Cartesian coordinates x and y. For those portions of the shock where this condition no longer applies, correction terms for the results obtained by Whitham's theory or even a higher order approximation would then be necessary.

3. It is concluded that because of the far-reaching effects of the intermediate field embodying flows of plane-wave character, there are interesting possibilities to influence the boom intensity. However, more extensive studies of the flow field must be undertaken first.

The significance of this paper lies in the finding that the representation of a delta wing with supersonic leading edges and constant loading by an equivalent body of revolution is valid in the near field only under certain conditions. This is especially significant in light of the conclusion that in many cases only near-field flows will be involved in the study of sonic boom due to the front shock.

G-50

A METHOD FOR WIND TUNNEL INVESTIGATIONS OF SONIC BOOM BASED ON LARGE MODELS

Y. S. Pan

AIAA Paper No. 71-184, Presented at AIAA 9th Aerospace Sciences Meeting, New York, New York, January 25-27, 1971

This paper presents a new method which allows the use of large wind-tunnel models to obtain far-field pressure signatures. The method is based upon a modification of Whitham's theory in the near-field which takes into account the three-dimensionality of the flow field near a complex model.

Based on linearized supersonic flow theory, the flow disturbance at the distance R in free flight is equal to the incident disturbance on the wall of a cylindrical supersonic wind tunnel of radius R.

Based on this, the author considers the flow external to a quasi-cylindrical streamtube enclosing the body of upstream radius R. A solution of the linearized potential equation which represents a disturbance propagating downstream from the quasi-cylinder was derived by Ward ("Linearized Theory of Steady High-Speed Flow," Cambridge University Press, London, 1955, Chapters 8 and 9) and is used here. The solution expresses the potential as a Fourier series in terms of the multipole distribution of the streamtube. The perturbation velocities are then found from this potential. The multipole distribution is then expressed in terms of the flow disturbances. This allows an exact relation between the flow disturbances and the corresponding local F-function on an arbitrary streamtube enclosing the body to be obtained, since the F-function is defined in terms of the multipole distribution. Since the streamtube of upstream radius R was chosen arbitrarily, the relationships derived are valid for any R within the linearized supersonic flow theory. Thus this method corrects the linear relation between the pressure disturbance and the local F-function to account for near field effects.

Based on Whitham's hypothesis on the improvement of the linear theory, the flow disturbances predicted by the linear theory propagate downstream along the exact characteristic curves. In the three-dimensional flow, the characteristic curve is replaced by a bicharacteristic curve. The direction of a bicharacteristic curve changes not only in the longitudinal sense but also in the azimuthal sense. The bicharacteristics are determined using the exact perturbation velocities (exact in the sense of being valid everywhere) and the conditions

$$\frac{\Delta x}{\Delta r} = \cot(\phi+\mu)/\cos\lambda$$

$$\frac{\Delta\theta}{\Delta r} = \tan\lambda/r$$

where x, r, θ are polar coordinates
ϕ = flow deflection angle
μ = Mach angle
and $\lambda = \tan^{-1}(w/v)$
w = perturbation velocity in θ direction
v = perturbation velocity in r direction

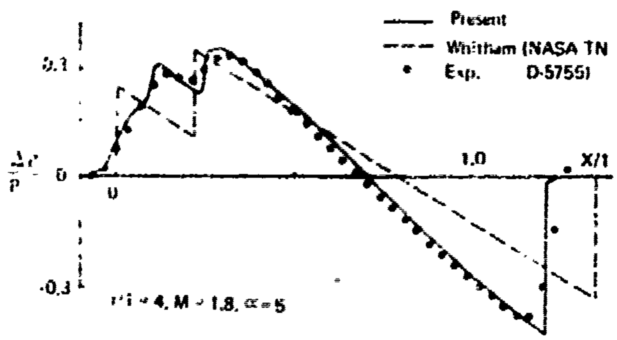
This results in parametric equations for x and θ in terms of r.

Since the values of the F-function are constant along bicharacteristics in the three-dimensional flow, a known F-function for one streamtube may be used to obtain a new F-function for a streamtube further afield. The shape of the F-function obtained at the larger radius is generally distorted from the original F-function. Multivalued regions are corrected by the insertion of shocks, which are found using the method of Whitham (see capsule summary G-3). Knowing the F-function at this larger distance allows the perturbation velocities, and thereby the pressure signature, to be calculated.

The relation between the free flight (incident) pressure distribution and the measured (reflected) pressure distribution on the cylindrical wind tunnel wall is then derived. This is done by solving the linearized potential equation together with the uniform free stream boundary conditions by using a Laplace transform technique.

To check the validity of the theory, comparisons are made with results calculated from Whitham's theory and with earlier experimental results. For a slender body of revolution at $r/\ell = 4.2$ (here ℓ

is the length of the body) and M = 1.2, both theories give good agreement with experiment. For a complex airplane model at r/ℓ = 4 at an angle of attack of 5° and M = 1.8 and 2.5, Whitham's theory gives poor correlation with the wind-tunnel measured signature while the signature obtained from an extrapolation of a measured signature at r/ℓ = 2 using Pan's method gives very good agreement with the measured signature, as shown in the figure below.



Signature comparison for complex airplane model

In an earlier paper Pan performed a similar derivation which was limited to slender bodies of revolution (see capsule summary G-48).

In a later paper Davis (see capsule summary G-69) used a bicharacteristic method to improve the location of the first order characteristics of slender bodies of revolution at high Mach numbers. His method differs from Pan's in that Pan not only corrects the location of the characteristics; he also corrects the linear relation between the pressure disturbance and the local F-function to account for near-field effects. Both theories agree on the fact that as the Mach number increases, the correction to the location of the first order characteristic increases.

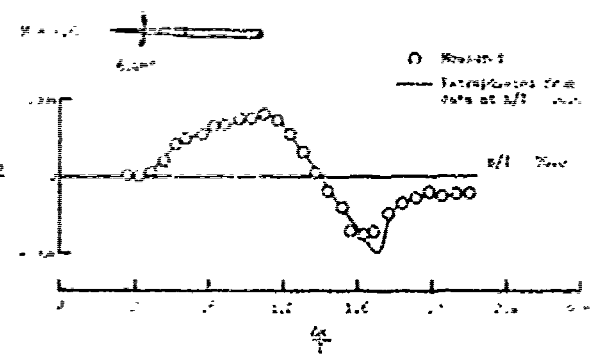
The excellent correlation between results calculated from this theory and experimentally measured results indicates that not only is it a valuable extrapolation technique which allows the use of large models in wind tunnels, it also provides increased accuracy over Whitham's method in the extreme near field of complex models whose F-function can be calculated.

This method should offer an improvement in the extreme near field of a complex model over the extrapolation technique developed by Hicks and Mendoza (see capsule summaries G-34 and G-51). Except for the extreme near-field, however, both methods should be equally valid.

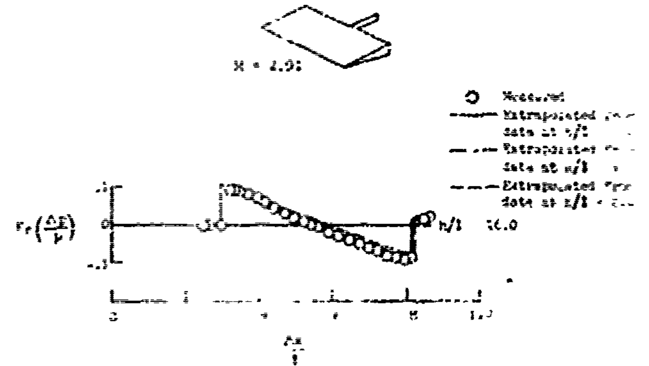
G-51
FURTHER STUDIES OF THE EXTRAPOLATION OF NEAR-FIELD OVERPRESSURE DATA
Joel P. Mendoza and Raymond M. Hicks
NASA TM X-2219, March 1971

The results of an experimental investigation into the range of validity of the extrapolation technique developed earlier by Hicks and Mendoza (see capsule summary G-34) are presented in this report. In particular, the applicability of the technique to configurations exhibiting large regions of two-dimensional flow, such as high aspect ratio wings and configurations with vertically displaced lifting elements resulting in considerable asymmetry of the flow field was investigated.

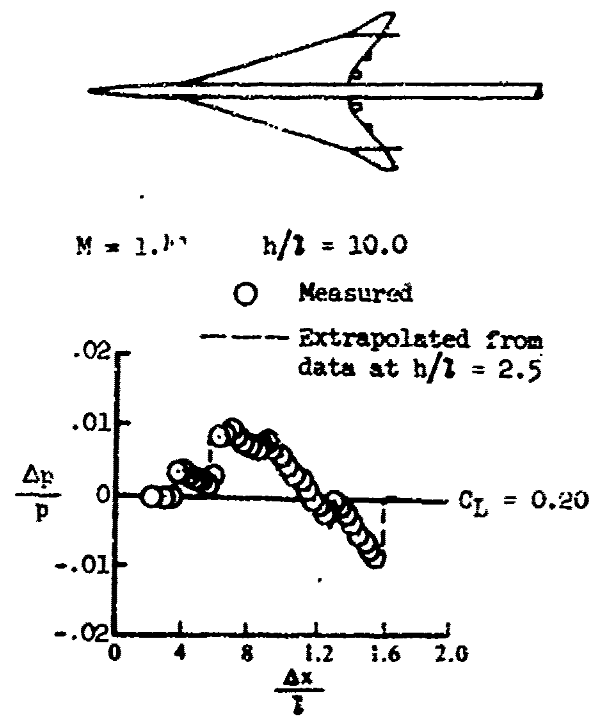
The pressure signatures of several different models were measured in the Ames 9- by 7-Foot and 8- by 7-Foot Wind Tunnels. Data from two previous wind tunnel tests was also used in the investigation. The models included cone-cylinders, rectangular planform wings, and complex airplane configurations. For each model the pressure signature was measured at various distance-to-length ratios. The signatures close to the model were used to determine extrapolated signatures at larger distances from the model, which were then compared with the measured signatures for those distances. In each case the agreement between measured signatures and extrapolated signatures was extremely good. Example correlations are shown below.



Correlation of measured and extrapolated signatures



Correlation of measured and extrapolated signatures



Correlation of measured and extrapolated signatures

The extrapolation technique investigated in this report was used in previous investigations by Hicks, Mendoza, and Hunton (see capsule summary G-33) and by Morris, Lamb, and Carlson (see capsule summary G-46). Both of these investigations found that this technique gave good results.

This paper gives a very convincing demonstration of the validity of using the extrapolation technique to predict the signature characteristics at larger altitudes using overpressure data measured at distances as close as one body length from an airplane configuration.

G-52
INVESTIGATION OF FLOW-FIELD DEVELOPMENT FOR A SERIES OF SONIC BOOM WIND TUNNEL MODELS
Harry L. Runyan, Herbert R. Henderson, Odell A. Morris, and Christine G. Pusey
NASA TN D-6143, March 1971

This report presents the results of a study conducted at a Mach number of 2.7 to study the growth of the pressure field as a function of distance from sonic-boom models. Six models four inches long were tested: two delta planforms and four rectangular planforms including one model with sideplates. The models had an upper surface aligned with the airstream and a lower lifting surface. The bottom surface on three of the models was made up of several steps.

Measured pressure signatures from these models were compared with calculated signatures based on two- and three-dimensional (Whitham) flow theories.

The results indicated a rapid transition from two-dimensional flow characteristics, known to exist near the model lower surfaces, to the three-dimensional characteristics measured in the tests. In general, good agreement was obtained, especially at the larger distances, between the measured pressure field and the pressure field calculated by use of conventional techniques for analysis of three-dimensional flow. The notable exception occurred for a model for which two-dimensional flow was forced to exist within the confines of sideplates. For that model, good agreement was obtained by use of theory for two-dimensional flow, particularly at the closest distance of about one body length. At the farthest measuring point, five body lengths, better agreement was obtained by use of three-dimensional flow theory. For the other models three-dimensional flow was established very rapidly, in most cases, in about one body length

A later investigation by Davis (see capsule summary G-56) dealt with the two-dimensional effects of high aspect ratio rectangular wings, in contrast to the low aspect ratio models used here. Davis found that Whitham's theory is not valid in the near field of high aspect ratio rectangular wings. However, Mendoza and Hicks (see capsule summary G-51) showed that their extrapolation technique, which is based on Whitham's theory, is valid at least as close as 16 body lengths from a rectangular wing of AR = 2.

This was the first wind tunnel investigation conducted to determine the distance from a body for which two-dimensional flow exists at which Whitham's theory is valid.

G-53
WIND TUNNEL INVESTIGATION OF SONIC-BOOM CHARACTERISTICS OF TWO SIMPLE WING MODELS AT MACH NUMBERS FROM 2.3 TO 4.63
David S. Miller, Odell A. Morris, and Harry W. Carlson
NASA TN D-6201, April 1971

The results of a wind tunnel investigation to determine high Mach number lift-induced sonic boom characteristics of two simple wing models, conducted at Mach numbers of 2.3, 2.96, 3.83, and 4.63 over a lift coefficient range from 0 to about 0.1 are reported. Comparisons of theoretical and experimental pressure signatures showed that the detailed signature shape was predicted to a greater degree of accuracy at the lower Mach numbers and lower lift coefficients. In all instances the overall signature correlation became worse as the Mach number and the lift coefficient increased. (For an illustration of this correlation, see capsule summary G-65.) It was noted, however, that at the higher lift coefficients where the experimental and theoretical signature shape differences were more pronounced, there was an unexpected improvement in maximum overpressure correlation. Although the generally observed tendency toward improved signature correlation with an increase in distance appears to be supported by the results of this investigation, the good correlation usually expected at large distances seems to be precluded by substantial differences between the experimental impulse and theoretical impulse. Impulse comparisons indicate that even at extremely large distances, experimental and theoretical overpressures would be expected to differ by as much as 20%.

A similar investigation concerning sonic boom tests of simple bodies of revolution at Mach numbers from 2.96 to 4.63 showed existing theories to be inadequate at high Mach numbers, especially for blunt-nose or small-fineness-ratio bodies (see capsule summary G-54). This paper extended the results to lifting bodies.

G-54

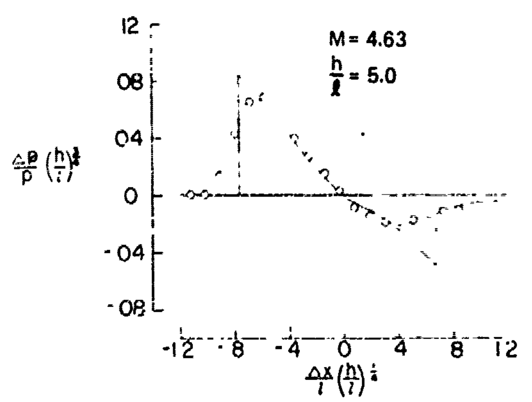
A WIND TUNNEL INVESTIGATION OF SONIC BOOM PRESSURE DISTRIBUTIONS OF BODIES OF REVOLUTION AT MACH 2.96, 3.83, AND 4.63

Barrett L. Shrout, Robert J. Mack, and Samuel M. Dollyhigh

NASA TN D-6195, April 1971

The validity of sonic boom theory for nonlifting bodies of revolution at high Mach numbers was investigated. This was accomplished by testing nine models in the Langley Unitary Plan Wind Tunnel at Mach numbers of 2.96, 3.83, and 4.63. The numerical methods developed by Carlson (see capsule summary G-23) and Middleton and Carlson (see capsule summary G-29) were used to calculate theoretical pressure signatures, which were compared with the measured signatures.

The results showed that as the Mach number increased, the far-field signature developed closer to the model. It was found that the sonic boom theory which gives good correlation between theory and experiment at low supersonic Mach numbers was only qualitatively correct for the higher Mach numbers of this test. An example of this correlation is shown below. In general the agreement between theory and experiment decreased with both increasing Mach number and decreasing model fineness ratio. In addition, the agreement between theory and experiment tended to decrease with increasing nose bluntness. The addition to the theoretical program inputs of a term accounting for the pressure distribution on the body improved the shape of the predicted signature and the addition of an estimated boundary layer improved the prediction of signature impulse. Estimation of the pressure signature using a nonsmooth-body method (see capsule summary G-3) produced a better correlation for the trailing shock, but some reduction of signature impulse.



Test-Theory Comparison for Cylinder With Conical Forebody

Miller, Morris, and Carlson (see capsule summary G-53) conducted a very similar investigation shortly after the one discussed here. In their investigation, however, lifting bodies at high Mach numbers were studied. The conclusions reached were basically the same as those reached here for nonlifting bodies. Hicks, Mendoza, and Hunton in an earlier investigation (see capsule summary G-33) also concluded that the validity of Whitham's theory decreases above Mach 3.0.

This investigation, along with the two discussed in the previous paragraph, demonstrated that, in spite of improved numerical methods for calculating the theoretical pressure signature, the sonic boom theory based upon Whitham's method decreases in accuracy above Mach 3.0. The accuracy also decreases with increasing body bluntness.

G-55

CALCULATION OF SUPERSONIC FLOWS AT LARGE DISTANCES FROM SLENDER LIFTING BODIES

Michael Schorling

NASA TN D-6446, August 1971

A second order solution of the supersonic flow in the far field of a slender lifting body with a nearly circular cross section is derived. The purpose is to derive a theory which can be used as the basis for handling such nonlinear effects as shock focusing or cutoff Mach number.

The exact nonlinear system of partial differential equations for supersonic flow is solved for large distances using a perturbation method developed by Poincare, Lighthill, and Kuo (see Tsien, H. S.: "The Poincare-Lighthill-Kuo Method." Vol. IV of Advances in Applied Mechanics, H. T. Dryden and Th. von Karman, eds., Academic Press, Inc., 1956, pp. 281-349). The unknown functions are expanded in perturbation series. This allows the nonlinear equations to be split into systems of quasi-linear differential equations of different orders of magnitude. These systems of equations are then integrated in each order of magnitude to obtain the unknown functions. The arbitrary functions of integration which result are determined by the boundary condition calculated from slender body theory. Use of this linearization is an approximation. A further approximation is necessitated by the fact that the boundary conditions are formulated at the body itself, while the equations were integrated for large distances away from the body. To overcome this difficulty the straight characteristics of zero order theory are matched at the distance R with those characteristics which result from the exact theory and which are valid for large distances. A discussion of the matching distance R is then presented.

The coordinates of the front shock wave are calculated using a three dimensional extension of Pfriem's formula or the "angle property" (see capsule summary G-3). The resulting equations are valid up to first order for general three dimensional flow and up to second order for axisymmetrical flow.

Example calculations are then made for two bodies of revolution and the results compared with Whitham's theory. The agreement is fairly good. However, the author emphasizes that the present theory has advantages such as simplicity of equations, handling of lifting bodies, and easy extension to more general problems as the change from a homogeneous to an inhomogeneous atmosphere.

Several other second order theories similar to this one had been developed previously. In 1968 Landahl, Ryhming, and Hilding (see capsule summary G-41) used the method of matched asymptotic expansions to develop a second order theory for two-dimensional flows and three-dimensional axisymmetric flows. They found, as did the present paper, that for nonaxisymmetric three-dimensional flow the lack of a near field second order solution made it impossible to obtain the far-field second order solution for such a flow. For a body of revolution it was found that second order effects are most important in the vicinity of the rear shock. Caughey in 1969 (see capsule summary G-44) also used the method of matched asymptotic expansions to derive second order solutions for planar flows and flows over bodies of revolution. A one-and-one-half order solution was derived for nonaxisymmetric three-dimensional bodies, but it was found that it offers no improvement over first order theory. In 1971 Lomax used a cathode ray display tube connected to a computer in connection with a finite difference method to find second order solutions for the flow over supersonic-edge delta wings (see capsule summary G-63).

In view of the finding by Landahl, Ryhming, and Hilding that second order effects are of most importance in the vicinity of the rear shock, the failure of the present investigation to deal with the rear shock is significant. Except for this omission, this is a very well done investigation.

G-56
INVESTIGATION OF SONIC BOOM GENERATED BY THIN, NONLIFTING, RECTANGULAR WINGS
Sanford S. Davis
NASA TN D-6619, December 1971

This report describes a new theory for predicting sonic boom pressure signatures produced by nonlifting rectangular wings. The purpose of this report is to evaluate signatures predicted by both this theory and Whitham's theory and to compare them with experimentally determined signatures.

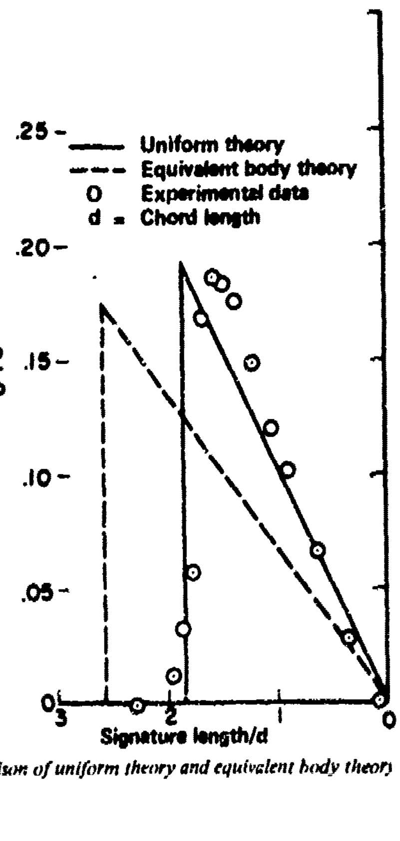
The author calls his theory the "uniform theory," since it is uniformly valid for the entire flowfield due to the fact that no large-distance assumption was made in deriving it. This theory is based upon Whitham's hypothesis, which states that linear theory gives a correct first approximation to variations of the physical quantities along the characteristics, but the location of these linearized characteristics is in error. In order to apply this hypothesis to the rectangular wing, it was necessary to obtain a better approximation to linearized theory than the one afforded by the equivalent body method. Therefore, instead of using the linearized theory expression for the potential due to a body of revolution the linearized perturbation velocity potential due to the presence of a nonlifting rectangular wing is used. (This means, of course, that no F-function is involved in this method.) The perturbation velocities, determined from this potential, are used to obtain a first order longitudinal correction to the characteristics. Shocks are inserted at the intersections of the characteristics so that the angle of intersection is bisected. Once the uniformly valid velocity field, including the shocks, has been obtained, the pressure rise at any point in the field is given by

$$\frac{\Delta P}{P_\infty} = -\gamma M^2 \frac{u}{V}$$

where ΔP = difference between local and static pressure
P_∞ = undisturbed free-stream static pressure
u = perturbation velocity in free-stream direction
and V = free stream velocity

A comparison of uniform theory with the equivalent body of revolution theory and with a series of experimentally determined near-field signatures showed that for low aspect ratio wings (i.e. less than one-half), both theories are in fairly good agreement with experiment.

For higher aspect ratio wings, with signatures taken in the vertical plane of symmetry, the uniform theory provides better agreement with experiment. The equivalent body theory overpredicts the signature lengths. However, it does predict peak overpressure with comparable accuracy to the new theory. These features are illustrated in the figure below, which was taken from this paper.



Comparison of uniform theory and equivalent body theory

With signatures taken in the horizontal plane of the wing, the two theories are in excellent mutual agreement, and, on the whole, are in reasonable agreement with experiment. No experiments were conducted in the far-field, but the theories give nearly identical results in this region of the flow.

In a previous investigation (see capsule summary G-51) Mendoza and Hicks found that their extrapolation technique could accurately predict the signature of a rectangular wing having an aspect ratio of 2 at a distance of 16 body lengths from the pressure signature measured at two body lengths. Thus, even though Whitham's theory may not be valid in the near field of a high aspect ratio wing, this extrapolation technique, which is based upon his method, is valid.

The theory described here, although an improvement over Whitham's theory, is highly restricted in utility due to the fact that it was derived strictly for a nonlifting rectangular wing.

G-57
A NEAR AND FAR-FIELD ANALYSIS OF THE SONIC BOOM EMITTED BY NONLIFTING RECTANGULAR WINGS
Sanford S. Davis
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 219-226

This paper presents the results of an experimental investigation into the validity of uniform theory (see capsule summary G-59 or G-56 for a discussion of this theory). These results are also discussed in capsule summary G-56.

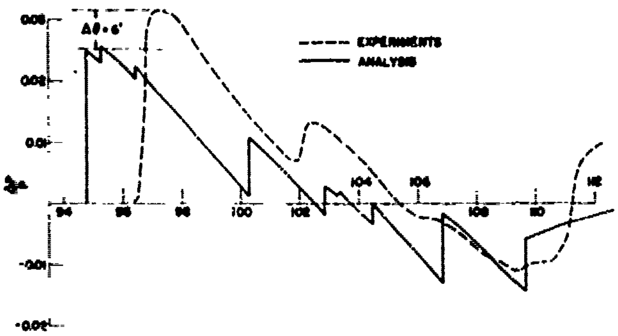
The experimental test program was conducted in the Ames 2X2 Foot Transonic Wind Tunnel at a Mach number of 1.4 using three nonlifting rectangular planform wings. The results show the predictions of uniform theory to be more accurate than Whitham's theory, especially for the higher aspect ratio wings (see capsule summary G-56 for an illustration of these results). The existence of rapid variations in near-field spanwise strengths and the subsequent smoothing effect of the tip cone interactions are also verified by the experimental results. The equivalent body theory, while giving erroneous results in the near field, predicts the far-field sonic boom below the wing very well.

The significance of this paper lies not only in the fact that it shows that uniform theory is valid in the near field of a high aspect ratio, nonlifting, rectangular wing, but also in its finding that Whitham's theory using the body of revolution equivalence is valid in the far-field of such a wing.

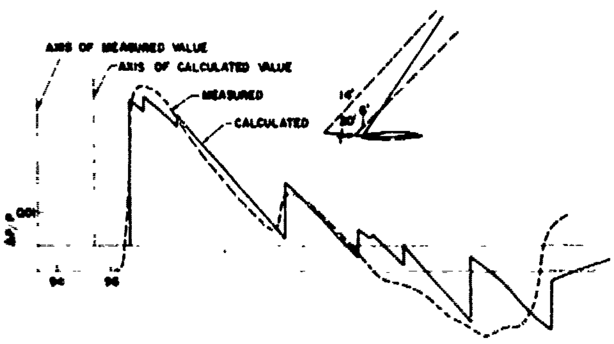
G-58
OBSERVATIONS ON PROBLEMS RELATED TO EXPERIMENTAL DETERMINATION OF SONIC BOOM
Antonio Ferri and Huai-Chu Wang
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 277-284

A discussion of the problems that affect the precision of wind-tunnel sonic boom experiments is presented in this paper. These problems include support interference, uniformity of flow, difficulties at high Mach numbers, Reynolds number effects, and three-dimensional effects.

It is shown that the presence of the sting and support changes the distribution of the cross-sectional area of the vehicle and wake and can produce large effects, especially when a near-field signature is present. Nonuniformities in the flow Mach number produce deviations in the overpressure and shock angle, which could be corrected for if a definition of these were known. It is stated that a variation of 0.01 in Mach number corresponds to $\Delta P/P$ = 0.011 at M = 2 and 0.015 at M = 4. The corresponding deviation of the Mach angle decreases with Mach number and goes from 16' to 3' (the prime denotes angular minutes not feet) as the Mach number increases from M = 2 to M = 4. These deviations tend to modify the position and strength of the shock, as shown in the first figure below. In the second figure a correction for a possible nonuniformity is introduced. The correction required is of 6' for the shock strength, plus an additional 14' for the position. Such variations are of the same order as the disturbances existing in the tunnel.



Sonic boom for h/L = 3.58 and M = 2.7



Sonic boom for h/L = 3.58 and M = 2.7

A brief mention is made of Reynolds number effects. The low Reynolds numbers of sonic boom tests make it important to take into account the possibility of laminar separation of the flow at the trailing and leading edges.

In conjunction with three-dimensional effects it is demonstrated that the equivalent body method may not be valid for supersonic leading edges. This is done by using the analytically determined signature of a 6° half-angle cone at a distance of five body lengths to compute an

equivalent body of revolution at two body lengths from the cone. The two stream surfaces produced by the deflection due to these two bodies are used to define two wings at a distance of three body lengths from the cone. This results in two wings having different planforms. If the equivalent bodies of revolution for each wing are determined at three body lengths, the two surfaces do not correspond to the same equivalent body in spite of the fact that they produce the same signature at five body lengths. The signature at a distance of 200 body lengths from the axis of the cone is different for the two surfaces and is different from the signature of the two equivalent bodies

This work was motivated by the desire to produce a specific near-field signature in the wind tunnel. The desired result was not achieved, and Ferri launched this investigation to determine why. The results are a good guide to the experimental difficulties involved in proving concepts such as low sonic boom configurations where the shock wave pattern can be significantly influenced by the tunnel nonuniformities, sting vibration, three-dimensional effects, etc.

G-59
UNIFORM APPROXIMATIONS FOR SHOCKS GENERATED BY THIN NONLIFTING RECTANGULAR WINGS
M. B. Friedman and S. Davis
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 123-132

This paper is essentially the same as the first half of a later paper by Davis (see capsule summary G-56). Basically, the method consists of using the perturbation velocity potential for a nonlifting rectangular wing instead of the perturbation velocity potential due to the equivalent body of revolution. The axial perturbation velocity is derived from this potential. To account uniformly to a first approximation for nonlinear effects, the bicharacteristics of linear theory are replaced by an approximation to the bicharacteristics of nonlinear theory expressed in terms of the axial perturbation velocity. The expressions for the axial perturbation velocity and the bicharacteristics represent the uniform first approximation to the velocity field. To complete the solution, shocks are inserted to separate the regions of disturbed and undisturbed flow and eliminate the regions of multivaluedness. The shock is positioned so that it bisects the characteristic directions that meet at a point.

Computations are then carried out and the results compared with those given by Whitham's theory. The reader is referred to capsule summary G-56 for a brief discussion of most of these results. The present paper discusses one aspect of the results in more depth, however. This is the comparison between the uniform theory (this paper) and nonuniform theory (Whitham) in predicting the variation of overpressure in various meridional planes. The nonuniform approximation always results in a monotonic distribution with a maximum occurring directly below the wing. However, for the larger aspect ratio wings, the uniform approximation shows a meridional distribution with both a maximum and a minimum occurring in some other meridional plane. This asymmetry tends to disappear as the aspect ratio decreases.

This paper demonstrates another case for which Whitham's theory is not valid, in addition to high Mach number flows and the extreme near field of complex models, and that is in the near field of a high aspect ratio, nonlifting rectangular wing.

G-60
REMARKS ON NONLINEAR EFFECTS
M. Landahl
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 407-408

This is a very brief discussion of the importance of nonlinear effects in sonic boom calculations, the success of second order theory in predicting these effects, and possible applications of the nonlinear solution for large distances.

It is the author's belief that there is not much hope of finding a reasonably simple second-order analytical solution for a general three-dimensional flow field and any good approximate theory would need to account for the deformation of characteristic surfaces.

G-61
NONLINEAR EFFECTS ON SONIC BOOM INTENSITY
M. Landahl, I. Ryhming, and P. Lofgren
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 3-15

The purpose of this paper is to show that the uniformly valid second-order solution of Lighthill ("Higher Approximations in Aerodynamic Theory," General Theory of High Speed Aerodynamics, W. R. Sears, ed., Princeton Univ. Press, 1954) for axisymmetric flow can be expressed in a very simple functional form. It is also shown that the second-order, three-dimensional, far-field solution expressed in cylindrical coordinates can be cast in a similar form but involves a readjustment of the angular coordinate as well.

A coordinate perturbation is applied to the second-order solution for axisymmetric flow in the manner of Lin (On a Perturbation Theory Based on the Method of Characteristics, J. Math. Phys., Cambridge, Mass., Vol. 33, No. 2, 1954) and Oswatitsch (Nonlinear Problems in Wave Propagation, Rept. SSS-67-74, Space Science Seminar, George C. Marshall Space Flight Center, 1967) so as to make both sets of characteristics appear as straight lines to first order. This made it possible to cast the results for the second order velocity components in very simple forms in which the first-order u-component is multiplied by the ratio of the free stream density to the local density. Here u is the dimensionless perturbation velocity component in the flow direction. The equation for the characteristics contains additional terms due to near-field effects which are not contained in Whitham's corresponding equation. It is then shown that the second order asymptotic solution for a nonaxisymmetric flow can be put in the same form as the axisymmetric uniformly valid one. The only difference is that the transformed

variables become somewhat modified to account for nonaxisymmetric effects.

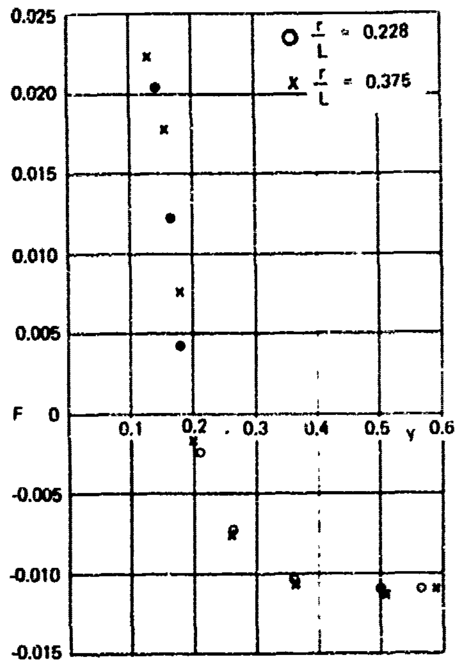
The second order solution is used to determine the effect of a small sourcelike perturbation on a nonaxisymmetric flow. A simple approximation is proposed that is likely to show small errors everywhere, which could be employed in a calculation scheme to build up a nonlinear flow field through step-by-step small perturbations.

The results of this paper, together with those of an earlier paper (see capsule summary G-41), are used to develop a new method for determining sonic boom strength from near-field measurements (see capsule summary G-62).

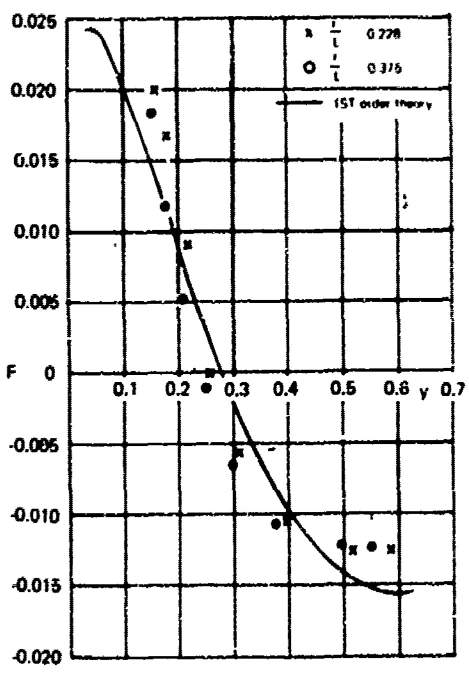
G-62
A NEW METHOD FOR DETERMINING SONIC BOOM STRENGTH FROM NEAR-FIELD MEASUREMENTS
M. Landahl, I. Ryhming, H. Sorenson, and G. Drougge
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 285-295

This paper presents a new method for determining the F-function based on accurate wind tunnel measurements of the flow inclination angles along a cylindrical surface that circumscribes the model. The derivation begins with the expressions for the first and second order perturbation velocities, the F-function, and the characteristics at large distances from a three-dimensional body in supersonic flow. These expressions were derived in another paper by Landahl, Ryhming, and Lofgren (see capsule summary G-61). The flow deflection angles ϵ (downwash angle) and σ (azimuthal deflection angle) are then related to the second order velocity perturbations and the second order velocity potential. These relations allow the F-function and the characteristics to be calculated from the measured flow deflection angles.

A wind tunnel test at M = 3.0 using a simple body of revolution was then performed to check the validity of this theory. The flow deflection angles were measured at distance-to-length ratios of 0.228 and 0.375. F-functions are calculated at each of these distances using both second order theory and first order theory. Those calculated from second order theory at these two radial locations are very nearly identical, indicating that the theory is valid. The F-curves determined from the tests according to first order theory (i.e., Whitham) differ, however, significantly from each other. There are also substantial differences between the second- and first-order predictions, as shown in the figures below.



Test results evaluated according to second order theory



Test results evaluated according to first order theory

Hicks and Mendoza (see capsule summary G-34) derived an extrapolation technique which used first order theory to calculate an F-function from a measured near-field pressure signature. The validity of their technique was demonstrated quite convincingly in subsequent experiments (see capsule summary G-51) for Mach numbers in the neighborhood of 2 or less. At high Mach numbers nonlinear effects are of greater importance, however, and it is in this regime that the new method described in this paper may prove to be of greatest utility.

The paper is weak in one area. The relations between the flow deflections and the velocity perturbations are derived for large distances from a three-dimensional body. Then when the wind tunnel experiment is performed with the axisymmetric body, measurements are made at distance-to-length ratios of 0.228 and 0.375, which certainly cannot be considered large distances. The authors fail to explain anywhere in the paper that for an axisymmetric body the various relations derived are uniformly valid for the entire flow field, as shown in an earlier paper (see capsule summary G-61). For a three-dimensional model the relations between the flow deflections and the perturbation velocities would only be approximate near the body. The closeness of the approximation remains to be checked.

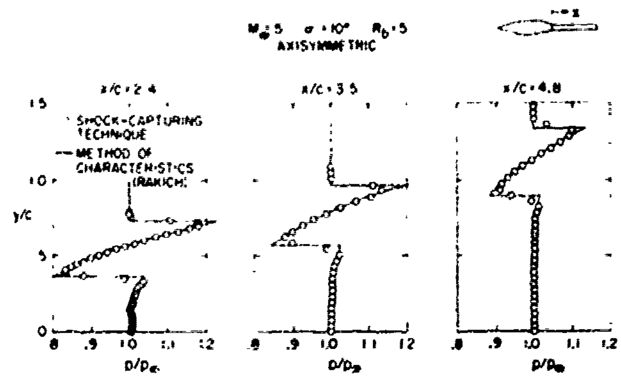
G-63
NUMERICAL SOLUTIONS FOR THE COMPLETE SHOCK WAVE STRUCTURE BEHIND SUPERSONIC-EDGE DELTA WINGS
Harvard Lomax and Paul Kutler
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 17-25

This paper presents the results of an investigation into the shock wave structure of various configurations by means of numerical finite difference methods carried out on a digital computer that is coupled with a cathode-ray display tube. This method was first discussed in an earlier paper by Lomax (see capsule summary G-42). The basic idea underlying this method is that the coalescing shock field surrounding not-so-slender wing-body combinations can be computed effectively if the calculations, as they are being carried out, are monitored by real-time reaction to visual displays.

The method relies upon what is referred to as a shock-capturing technique. Using this technique, the initial data is advanced through a fixed mesh, applying boundary conditions only at the body and in the free stream. Shock and expansion waves form and decay automatically without special treatments of any kind. A second order finite difference scheme is used in conjunction with this technique to solve the gas-dynamic equations.

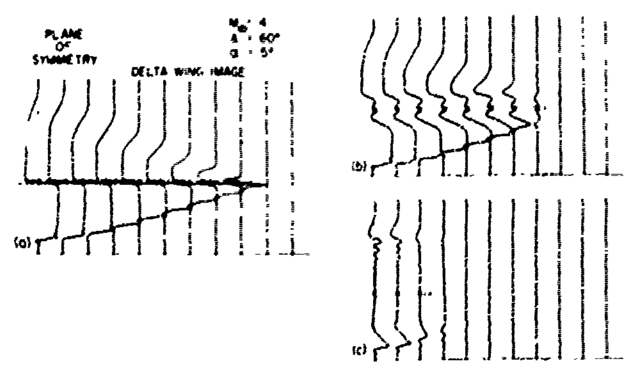
Confidence in this method is established by using it to compute a variety of known flow fields obtained from experiment or from calculations made using such techniques as the method of characteristics.

Those flow fields included those due to wedges, cones, planar delta wings, delta wings with dihedral mounted on conical bodies, two-dimensional airfoils, axisymmetric bodies, and the completely three-dimensional flow behind a lifting delta wing with supersonic leading edges. The results of a comparison with the other methods show that good agreement is obtained for all cases, except one, between the predictions of this method and the other techniques. The lone exception is a disagreement between the results of this method and linear theory for the pressure distribution on a lifting planar delta wing. An example of the good correlation obtained for the other cases is shown in the figure below.



Pressure distribution along vertical lines behind a pointed ogive

The figure below, which was also taken from this paper, is a reproduction of a sequence of photographs taken from the cathode-ray display tube as the flow field developed behind the lifting planar delta wing. In figure (b), the formation of the trailing edge shock is clearly evident in the expansion region above the delta-wing image, as is the trailing edge expansion fan below the delta-wing image. The governing equations were solved in conical coordinates, thus giving the appearance of a shrinking wing as the integration proceeds downstream.



Normal pressure distributions behind planar delta wing

This was one of the first numerical implementations of a second order technique.

G-64

ON THE EXTRAPOLATION OF MEASURED NEAR-FIELD PRESSURE SIGNATURES OF UNCONVENTIONAL CONFIGURATIONS

Joel P. Mendoza and Raymond M. Hicks

NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 385-392

This paper shows that the near-field extrapolation technique of Mendoza and Hicks gives accurate results in many cases for which Whitham's theory based on theoretically derived F(y) functions does not. For details of this technique see capsule summary G-34.

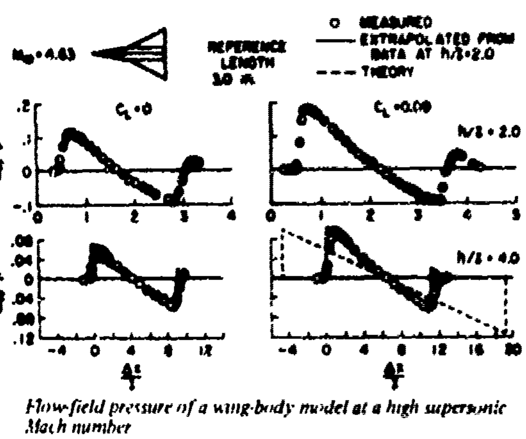
The configurations studied in this paper included a 6.48° cone-cylinder model and two models of the straight-wing and delta-wing orbiters. Overpressure data on a wing-body and two wing-alone models was obtained from previous investigations.

For each model, overpressure characteristics measured at some given altitude were extrapolated and compared to overpressure characteristics measured at a higher altitude. In cases for which the Whitham theory was considered applicable, a theoretical pressure signature is compared with the extrapolated and measured data.

For the cone-cylinder, theory, the extrapolated signature, and the measured pressure signature were all in excellent agreement at a distance of 20 cone lengths. This was expected, since Whitham's theory was formulated for an axisymmetric body.

No comparison with theory was made for the two wings, which had aspect ratios of 2 and 1/2. For the AR = 1/2 wing, the measured and extrapolated signatures showed excellent agreement at a distance of eight chord lengths. For the AR = 2 wing, which was expected to retain its two-dimensional flow-field characteristics at a larger distance from the wing plane than the other wing it was found that pressure signatures extrapolated from signatures measured at successively increasing distances from the model exhibited successively improved correlations with the data measured at the altitude of 16 chord lengths.

For a wing-body model at a Mach number of 4.63, both the extrapolated data and the theoretical pressure signature agree fairly well with the measured data at an altitude of four body lengths at zero lift coefficient. At a lift coefficient of 0.09, however, theory predicts a longer pressure signature length, as shown in the figure below.



Flow-field pressure of a wing-body model at a high supersonic Mach number

The measured and extrapolated pressure signatures of the straight-wing and delta-wing orbiters at a Mach number of 2.7 and an angle of attack of 60°, for which condition a strong bow shock existed, showed excellent agreement.

In another paper (see capsule summary G-51) Mendoza and Hicks give additional proof of the validity of their technique.

G-65

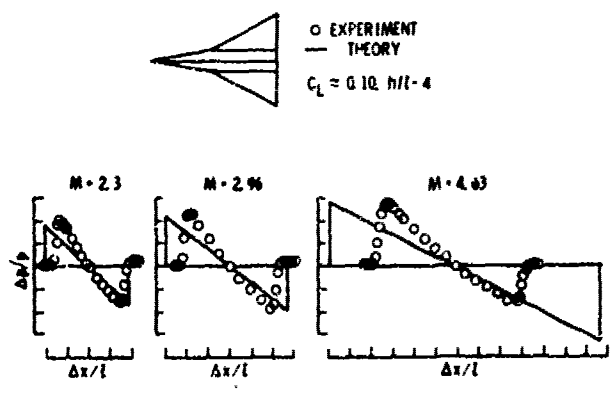
EXPERIMENTAL STUDIES OF SONIC BOOM PHENOMENA AT HIGH SUPERSONIC MACH NUMBERS

Odell Morris

NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 193-203

This report reviews the results of two sonic boom studies which investigated the validity of sonic boom theory at high supersonic Mach numbers. In these investigations measured wind tunnel signatures were compared with theoretical signatures calculated using machine computing programs which account for volume, lift, and interference effects.

The results showed that the theoretical methods for predicting the pressure signatures were only qualitatively correct at the high Mach numbers. In general, it was found that the agreement between theory and experiment decreased with both increasing Mach number and increasing lift coefficient. The Mach number effect is illustrated in the figure below, which was taken from this paper.



Mach number effect

The results discussed briefly in this paper are covered in much more depth in the papers summarized by capsule summaries G-53 and G-54. This paper does give a good quick summary of both of these reports, however.

G-66

ON THE ANALYTICAL METHOD OF CHARACTERISTICS

Helge Norstrud

NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 421-425

This paper expresses the need for analytical methods for the near-field region about arbitrary aircraft configurations and labels the available theories either too cumbersome (e.g., method of characteristics) or too limited in application (Whitham's theory). An analytical method of characteristics is described which

the author believes has the potential of yielding improvements in both areas of concern.

The analytical method of characteristics described is that of Oswatitsch. This technique expresses the physical coordinates of the characteristic space and the dependent variables (kinematical and state quantities) in a series form of, in general, increasing order terms of some small perturbation parameter. These series are then substituted into the hyperbolic system under consideration, and the physical coordinates are obtained by integration along the bicharacteristic lines. The dependent variables for given boundary and initial conditions (written in the characteristic space) are found from the compatibility relations. This procedure is then repeated in an iterative manner until the desired degree of accuracy is reached.

The author concludes by saying that this method is fundamental to any study of supersonic flow and should not be overlooked in the theoretical aspect of the sonic boom problem.

This paper makes a good case for the importance of Oswatitsch's method, but the degree of improvement to be expected in numerical calculations is not established.

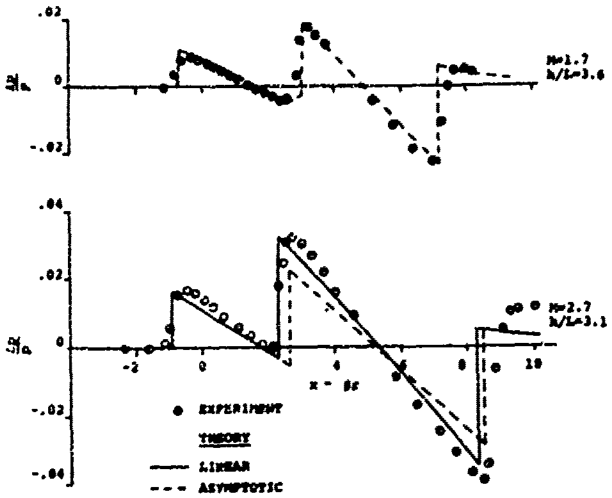
G-67
MEASURED AND CALCULATED SONIC BOOM SIGNATURES FROM SIX NONAXISYMMETRIC WIND-TUNNEL MODELS
H. L. Runyan, H. R. Henderson, O. A. Morris, and D. J. Maglieri
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 341-350

This paper is exactly the same as NASA TND-6143, which is discussed in capsule summary G-52, except that this paper does not contain the detailed model drawings of the former. The reader is referred to capsule summary G-52 for details of this paper.

G-68
PRESSURE SIGNATURE ESTIMATION AT HIGH MACH NUMBERS
Frank A. Woodward
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 437-441

This paper presents a brief discussion of a method which offers an improvement over Whitham's theory in the extreme near field at high Mach numbers. In this method the body is represented by a system of line sources and doublets located along the configuration axis, and the wing is represented by source and vortex distributions located on panels in the plane of the wing. Interference effects between the wing and body are accounted for by additional vortex panels on the body surface aft of the wing leading edge. Linear theory is then used to calculate the pressure disturbances due to these singularity distributions.

A comparison between results predicted by this theory and Whitham's theory with measured results shows that in the extreme near field of a cone cylinder this method gives a better estimate of the magnitude of the front shock wave and the rate of flow expansion behind it than Whitham's theory, especially at high Mach numbers. For a delta wing body combination at a Mach number of 1.7 at a distance-to-length ratio of 3.6, Whitham's theory shows excellent agreement with experiment. For the same configuration at a Mach number of 2.7 at a distance-to-length ratio of 3.1 the linear theory used here gave much better correlation with experiment than Whitham's theory, as shown in the figure below.



Effect of Mach number on the near field pressure signatures of a delta-wing body combination

An earlier paper by Woodward also deals with the method discussed here (see capsule summary G-32). The improvement in agreement between experiment and theory as a result of using this method is due mainly to a more accurate determination of the body and wing perturbation velocities.

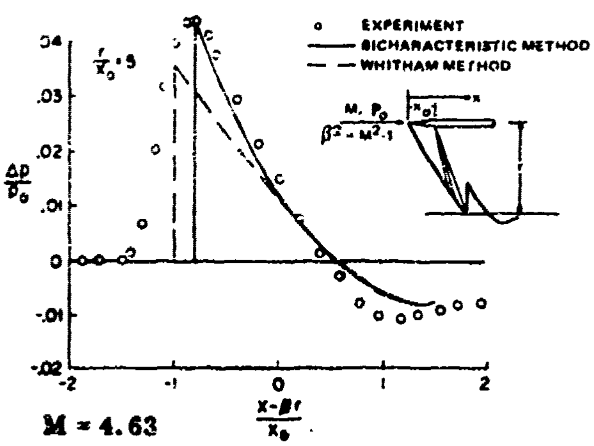
G-69
CALCULATION OF SONIC BOOM SIGNATURES BY CHARACTERISTIC METHODS
Sanford S. Davis
AIAA Paper No. 72-195, AIAA 10th Aerospace Sciences Meeting, San Diego, California
January 17-19, 1972

The purpose of this paper is to show that, for slender bodies, the major cause of the discrepancy between Whitham's theory and experimental results at high Mach numbers is the imprecise location of the first order characteristics. Whitham's method corrects only the streamwise variable, whereas in the method derived here the first order bicharacteristic lines are obtained by correcting all of the independent variables simultaneously. (The bicharacteristics are space curves which form the generators of the characteristic surface of the characteristic partial differential equation.) To simplify the manipulations, the procedure is applied to a slender body of revolution, reducing the number of independent variables to two.

Starting with the equations of motion, a perturbation series method is used to calculate the bicharacteristics to terms of $O(\epsilon)^2$, where ϵ is a small length parameter of the body. The perturbation velocities are expressed in terms

of the F-function of the body, using exactly the same method that Whitham used. The bicharacteristics are expressed parametrically by giving the values for the streamwise and radial variables (x and r) in terms of the distance t along the curve. The expressions for both x and r contain corrections for nonlinear effects, whereas Whitham corrected only the value of x. The shock waves are fitted into the field of bicharacteristics by applying the Rankine-Hugoniot shock relations. The pressure field is determined from the streamwise perturbation velocity and the F-function using Whitham's general formula (see capsule summary G-3).

The theory is then applied to the case of a slender cone-cylinder. A comparison with experimental results and Whitham's theory showed that the bicharacteristic method gives better agreement with experiment at higher Mach numbers, as shown in the example figure below. It should be noted, however, that the bicharacteristic method still gives a significant underprediction of the signature impulse.



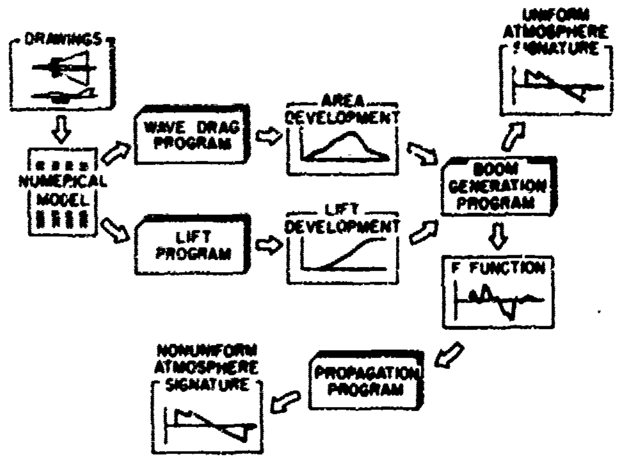
Comparison of bicharacteristic method and Whitham's theory

In another paper (see capsule summary G-56) Davis uses an improved version (as compared to the equivalent body method) of linear theory for a nonlifting rectangular wing to correct the characteristics. This contrasts with the method used in the present paper, which uses the normal F-function form of the linearized solution throughout.

Although this method does offer an improvement over Whitham's theory at high Mach numbers, the improvement is not substantial when compared to measured data.

G-70
REVIEW OF SONIC-BOOM GENERATION THEORY AND PREDICTION METHODS
H. W. Carlson and D. J. Maglieri
The Journal of the Acoustical Society of America, Vol. 51, No. 2 (Part 3), February 1972, pp. 675-685

The state of the art of sonic boom generation theory as of 1970 is reviewed briefly in this paper. The concepts underlying Whitham's theory (see capsule summary G-3) and Hayes' supersonic area rule (see capsule summary G-1) are discussed first. The use of a computer to implement these methods for realistic airplane configurations is then discussed. The various programs used at the NASA Langley Research Center in each step of the procedure are listed. These are shown schematically in the figure below, which was taken from this paper.

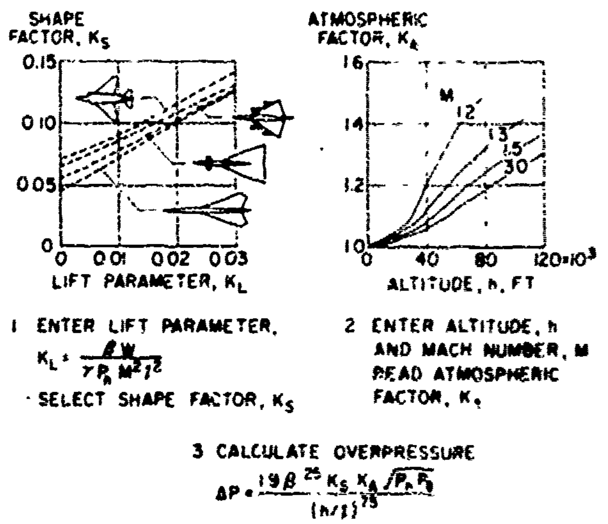


Computer Employment in Sonic Boom Analysis

The first step in this procedure is to prepare a numerical model of the configuration to be treated. This consists of tabulations of the aircraft geometrical characteristics. The wave drag program developed by the Boeing Airplane Company (see capsule summary G-22) is then used to obtain the area development of the airplane for the desired Mach number and azimuthal angle. A computing program for the determination of linearized theory loadings on twisted and cambered wings of arbitrary planform (see "Numerical Method of Estimating and Optimizing Supersonic Aerodynamic Characteristics of Arbitrary Planform Wings," by Wilbur D. Middleton and Harry W. Carlson, J. Aircraft, 2, 261-255 (1965)) is used to determine the lift development of the airplane. Interference effects are evaluated by an auxiliary program (see Robert J. Mack, "A Numerical Method for Evaluation and Utilization of Supersonic Nacelle-Wing Interference," NASA TN D-5057 (1969)). After some manual work, the equivalent body area development is fed into the sonic boom generation program (see capsule summaries G-15 and G-29). This program implements Whitham's method and includes a numerical solution for the area balancing required in the determination of shock location and strength and provides a complete uniform atmosphere signature. It also generates an F-function which can be used in the Hayes computer program (see capsule summary P-58) to generate a pressure signature which takes into account changes brought about by its propagation through an arbitrary stratified atmosphere with or without winds.

The results of previous wind tunnel tests and flight tests conducted to determine the applicability of these techniques are discussed briefly. It is concluded that they are capable of providing reasonably accurate predictions of overpressures for moderate supersonic speeds. Applicability of the prediction techniques at Mach numbers above 3 had not been thoroughly explored and it is stated that there is clearly a need for further research in the hypersonic speed regime.

A sonic-boom bow shock overpressure estimation technique is given. Using this method the overpressure of an arbitrary configuration can generally be determined within 20%. The method is illustrated in the figure below.



"First Cut" sonic boom estimation

Previously Carlson had given state-of-the-art summaries for 1964, 1967, and 1968 (see capsule summaries G-25, G-35, and G-39, respectively). This paper updates these through 1970.

As stated by the authors, this review is intended to serve as an introduction to prediction techniques and to provide an understanding of sonic boom generation and propagation phenomena for the general reader and for specialists in other areas of sonic boom research who are not involved in calculating pressure signatures. As a result the subject treatment is broad and conceptual rather than mathematical.

G-71
SONIC BOOM OF HYPERSONIC VEHICLES
Y. S. Pan and W. A. Sotomayer
AIAA Journal, 10(4), 550-551, April 1972

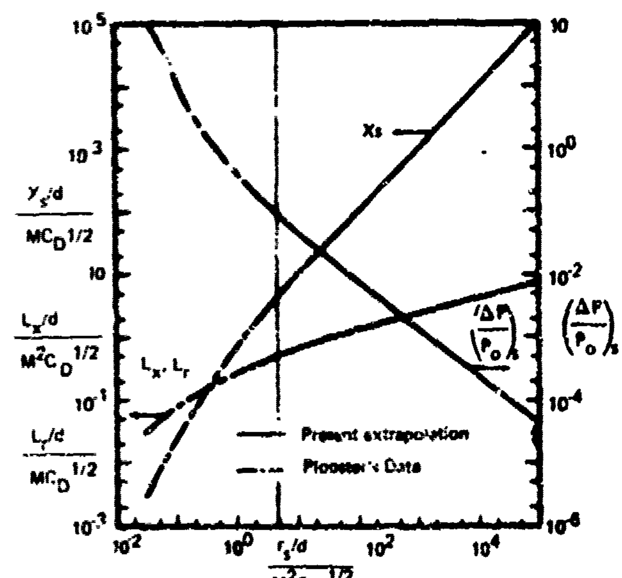
This short note presents an approximate method for determining the far-field flow pattern of hypersonic bodies. The flow disturbances in the far-field are taken, as a first approximation, to be equal to the disturbances produced by an equivalent body of revolution having experienced the same total drag as the actual body. The equivalence of the hypersonic flow over a blunt-nosed axisymmetric slender body having a long cylindrical afterbody (representative of the viscous wake) to the constant energy cylindrical blast wave problem is then used. Numerical solutions obtained by Plooster in the weak shock region for cylindrical shock waves from line sources were then matched with the solution given by Whitham's weak shock theory (see capsule summary G-3). Complete pressure signatures can then be obtained at any greater distance. The resulting expression for the sonic boom shock overpressure is:

$$\left(\frac{\Delta P}{P_o}\right)_s = 0.306\,\frac{MC_D^{1/2}}{r_s/d}\left[\frac{(r_s/d)^{1/2}}{M^{1/2}C_D^{1/4}} - 0.721\right]^{1/2}$$

where P_o = a reference pressure
M = Mach number
C_D = drag coefficient
d = body dimension
r_s = radial distance from body

Expressions are also derived for the shock location and positive phase duration.

A numerical example is then given of the positive phase signatures of a hypersonic vehicle in steady level flight. The results indicate that the general behavior of the sonic boom during steady level flight is consistent with that of the sonic boom of supersonic vehicles. That is, the larger the Mach number, the larger the drag coefficient, or the lower the altitude, the larger are the sonic boom overpressure, positive duration, and sonic boom impact. These results are illustrated in the figure below.



Sonic boom overpressure $(\Delta P/P_o)_s$, position X_s, and positive phase duration L_r or L_x vs shock radius r_s

In a previous paper, Seebass (see capsule summary G-47) used a different approach and obtained an expression for the bow shock overpressure which takes into account atmospheric stratification.

G-72

THE WAVE FORMATION AND SONIC BOOM DUE TO A DELTA WING

K. Oswatitsch and Y. C. Sun

The Aeronautical Quarterly, Volume 23, May 1972, Part 2, pp. 87-108

This paper is very similar to an earlier paper by Oswatisch and Sun (see capsule summary G-49), except that a flat delta wing with supersonic leading edges is used here instead of a delta wing with uniform loading. The analytical method of characteristics is used again here (see capsule summary G-49).

The analysis is confined to the determination of the front shock in the vertical plane of symmetry. Air stratification is not taken into account. The influence of spatial flow on the wave front of the plane of symmetry is considered briefly, and it is concluded that an analysis of the characteristics in this vertical plane alone is sufficient.

The results of the study show that in the vertical plane of symmetry below the wing a full cancellation of the front shock will usually be effected at a finite distance from the wing by the plane-wave expansion emanating from the trailing edge. Beyond the terminating point of the front shock, no sharp-front wave signature can be expected from the wing, and the boom signature will begin with a gradual rise of suction. This difference from the signature due to a body of revolution is important from the standpoint of sonic boom analysis, since the type of pressure increment plays a significant role in defining the effects of sonic boom. Another result is that the shape of the planform of the wing may exert considerable influence on the front shock as well as the rear one. It is concluded that the nonequivalence of a wing to a body of revolution in the far-field implies that, for a wing of finite aspect ratio, a correct description of the far-field can only be arrived at by taking the near- and intermediate-fields properly into account.

The results of this paper differ from the previous paper by Oswatitsch and Sun in that this paper shows that the delta wing is not equivalent to a body of revolution, even in the far-field, while the previous paper found that in the far-field the delta wing could be represented by a body of revolution. This is not due to any errors in the earlier paper. It is a result of a more extensive investigation of the flow-field development in this paper.

The finding that the front shock is cancelled at a finite distance from the delta wing is of tremendous potential significance. However, the fact that such a cancellation has never been experimentally verified raises questions as to the validity of this finding. This analysis considers only a lifting membrane in a uniform atmosphere. The following have not been considered and these might have significant influences regarding their conclusions:

1. The effect of aspect ratio has not been considered. The conclusions regarding the cancellation of the front shock may be a fairly strong function of the aspect ratio. Most supersonic airplanes have an aspect ratio of less than 2.
2. There is no consideration of the influence of the volume of the wing. This influence should be considered in that it produces shock waves at both the leading and trailing edges which will interact with the lift-induced pressure field. This undoubtedly has a significant effect.
3. There is no consideration of the influence of the stratification of density and temperature in the media. Hayes has shown that this influence is to slow the aging (or development) of the pressure field. For instance, at Mach 2.7 the pressure signature in the standard atmosphere that has propagated 60,000 feet will look as if it had only propagated 27,000 feet in the uniform atmosphere. That is, the effect of stratification is to retard or inhibit the coalescence of the shock waves and the pressure signature. Hence the point where the front shock disappears may never be reached in the real atmosphere. This influence must also be considered.

The analysis method looks very promising in terms of improving the accuracy of predictions made for airplane configurations (3-D objects) but the above-mentioned influences must be taken into account before any numerical results can be quoted with any degree of confidence.

G-73

A FLIGHT TEST INVESTIGATION OF THE SONIC BOOM

Marshall E. Mullens

Air Force Flight Test Center, Edwards Air Force Base, California, AFFTC-TN-56-20, May 1956

In the investigation discussed in this paper, flight tests were conducted to measure the sonic boom generated by an F-100 in level supersonic flight. Data was obtained at Mach 1.05 at two altitudes, 25,000 and 35,000 feet by flying a second F-100, instrumented for static pressure measurements, through the shock wave pattern of the test aircraft. The separation distance between the two aircraft varied between 100 and 2000 feet.

The following conclusions were reached as a result of this investigation:

1. The initial rate of decay of the strength of bow shock versus distance was found to be quite large and in accordance with Whitham's asymptotic formula (see capsule summary G-3).

2. It was concluded that the pressure rise at ground level for very low altitude supersonic flight can be as much as 60 psf.

3. It was concluded that high Mach number airplane fly-bys are potential safety hazards and should be approached with caution.

4. The occurrence of the sonic boom at ground level was found to be dependent upon the prevailing atmospheric conditions and, therefore, difficult to predict.

The main significance of this investigation is that it was the first attempt to verify sonic boom theory using actual flight-test measurements. However, this investigation was not as extensive as many similar later investigations (see capsule summaries G-9, G-12, and G-16, for example).

G-74

THE AERODYNAMICS OF THE SUPERSONIC BOOM
Harry W. Carlson
IAS Paper No. 59-115, Presented at the IAS National Summer Meeting, Los Angeles, California, June 16-19, 1959

This paper is an abbreviated version of a later paper by Carlson (see capsule summary G-7). The reader is referred to the capsule summary of that paper for details.

G-75

A WIND TUNNEL INVESTIGATION AT A MACH NUMBER OF 2.01 OF THE SONIC BOOM CHARACTERISTICS OF THREE WING-BODY COMBINATIONS DIFFERING IN WING LONGITUDINAL LOCATION
Odell A. Morris
NASA TN D-1384, Sept. 1962

This paper presents the results of a wind tunnel investigation concerning the influence of configuration design on the sonic boom intensity. Three wing-body configurations having different longitudinal locations of the wing were tested at Mach numbers of 2.01. Measurements of the pressure fields generated by the models (fuselage length of 1 inch) were made for three different horizontal positions at stations up to 50 body lengths from the models and for lift coefficients up to 0.2.

The measured bow shock overpressures, after being adjusted to account for model vibration using the method described in capsule summary G-18, were compared with theoretical values calculated using Whitham's asymptotic formula (see capsule summary G-3) and an F-function derived by Walkden (see capsule summary G-6) which accounts for both lift and volume effects. It was found that, for all three configurations, most of the theoretically computed points fell within a range of ±15 percent of the adjusted bow shock pressures.

This study demonstrated the essential validity of the Whitham-Walkden theory in predicting the change in bow shock overpressure caused by a change in configuration variables.

G-76

A NOTE ON THE SONIC BANG WAVEFORM OF AN AIRCRAFT WITH LIFT
C. H. E. Warren
Journal of The Royal Aeronautical Society, Vol. 67, September 1963, p. 595

This short note discusses the sonic boom pressure signature of a lifting aircraft. The main point made is that, even for an aircraft with lift, at large distances from the flight path the pressure jumps associated with the bow and stern shocks of the N-wave are equal and the positive and negative phases are of equal duration. The lift is associated with a contribution to the pressure which is negligible at large distances.

Sigalla (see capsule summary G-17) showed in an earlier paper that the transfer of lift to the ground can be accounted for when the complete linear theory is used to compute the pressure field rather than the asymptotic approximation to linear theory used by Whitham.

G-77

LIFT PRODUCED BY A SONIC BOOM
A. Sigalla
Journal of the Royal Aeronautical Society, Vol. 67, December 1963, p. 796

This short note points out that the question raised by Warren (see capsule summary G-77) concerning the transfer of lift from an aircraft to the ground was answered in a previous paper (see capsule summary G-17) by the author of the present paper. In his paper Warren pointed out that the lift is associated with a contribution to the pressure field which is negligible at large distances, which makes it extremely difficult to determine the lift from a knowledge of the pressure distribution in the far field. However, this was done in a very straightforward manner by Sigalla in his earlier paper. The reader is referred to the capsule summary of that paper for details.

G-78

NOMOGRAMS FOR DETERMINING SONIC BOOM OVERPRESSURE
Charlie M. Jackson, Jr. and Harry W. Carlson
Journal of Aircraft, Vol. 3, No. 1, Jan.-Feb. 1966, pp. 74-76

This short note presents two nomograms which can be used to estimate the asymptotic bow shock overpressure of an aircraft once its Mach number, flight altitude, length, and weight are known. The nomograms were derived using data for current (1966 and older) airplane configurations which restricts the application to conventionally designed airplanes.

G-79

SONIC BOOM OF BODIES OF REVOLUTION
K. Oswatitsch
Aircraft Engine Noise and Sonic Boom, AGARD Conference Proceedings No. 42, May 1969, pp. 11-1 through 11-9

This paper presents a brief outline of work that was being done concerning sonic booms at the DVLR - Institute of Theoretical Gasdynamics in Germany. The problems briefly touched upon using the aid of an analytical method of characteristics are:

1. The sonic boom generated by inclined and non-inclined bodies of revolution moving at a constant supersonic speed.

2. The sonic boom generated by a non-inclined body of revolution moving at an increasing or decreasing transonic speed.

3. The influence of the isothermal stratification of the atmosphere on the sonic boom.

In later papers (see capsule summaries G-49 and G-72) Oswatitsch and Sun use the analytical method of characteristics to investigate the sonic boom due to a lifting delta wing.

G-80

ON THE EXPERIMENTAL DETERMINATION OF THE NEAR-FIELD BEHAVIOR OF THE SONIC BOOM, AND ITS APPLICATION TO PROBLEMS OF N-WAVE FOCUSING
Donald J. Collins
AIAA Paper No. 71-85, Presented at AIAA 9th Aerospace Sciences Meeting, New York, New York, January 25-27, 1971

This paper describes an experiment conducted in a free-flight ballistics range constructed in the Guggenheim Aeronautical Laboratory at the California Institute of Technology. There were two parts to the experiment. The purpose of the first part was to examine in detail the behavior of the sonic boom generated by a non-lifting, axially symmetric projectile in a homogeneous atmosphere in order to determine the degree to which Whitham's asymptotic theory (see capsule summary G-3) is valid in the mid- and near-fields, before the pressure signature has attained its asymptotic form. The purpose of the second portion of the experiment was to examine the intensification and attenuation of the sonic boom by its interaction with obstacles. Only the results of the first portion of the experiment will be summarized here. For a discussion of the second portion of the experiment, the reader is referred to capsule summary P-116.

The projectiles used in this experiment were standard 110 grain hollow point and 180 grain flat based Spitzer 308 caliber bullets. They were fired from a Model 1903-A3 National Ordnance 30-06 barreled action mounted from the ceiling of the laboratory. The projectile Mach numbers were varied within the range $1.1 \leq M \leq 2.6$ by controlling the type and amount of powder used in each round. Pressure signatures were measured at radial distances of $3.0 \leq R/L \leq 100$, where R is the radial distance from the projectile flight path and L is the projectile length.

The measured bow shock overpressures, signature length, rate of pressure fall between shocks, and rear shock overpressure were compared to the theoretical values predicted by Whitham's asymptotic theory. The agreement was found to be within 10% for all quantities at a distance of $R/L = 10$, despite significant evidence of mid-field effects in the N-wave signature. As expected the agreement improved with increasing distance, and at a distance of $R/L = 100$ the measured and calculated values were essentially the same.

In a much earlier investigation (see capsule summary G-14) Kane also used a ballistic range to investigate the range of validity of Whitham's asymptotic theory. He found, in agreement with the earlier results of Du Mond, et. al. (see capsule summary P-2), that the point at which essential agreement was obtained between the measured results and the values calculated from Whitham's asymptotic theory was at about $R/L = 100$. However, in the present investigation more extensive measurements of the near-field were made than in the earlier investigation.

This was a significant investigation because it was the first to obtain sufficient data throughout the mid- and near-field range to determine the complete manner in which Whitham's asymptotic theory becomes less accurate as distance from the body decreases.

G-81

AN IMPROVED METHOD FOR CALCULATING SUPERSONIC PRESSURE FIELDS ABOUT BODIES OF REVOLUTION
Robert J. Mack
NASA TN D-6508, October 1971

This paper presents an improved near-field method for calculating the sonic boom pressure signature at high supersonic Mach numbers of a body of revolution. When Whitham derived his general (near-field) theory (see capsule summary G-3) an approximate equation for the characteristics (i.e., the loci of points influenced by a given source distribution) was used. This approximation resulted from the assumption that $\beta r/y$ was large, where $\beta = \sqrt{M^{2-1}}$, r is the radial distance from the flight path, and y is the distance from the nose of the body at which the specified characteristic intersects the body axis. In the present paper this assumption was not made. Thus the expression for the characteristics is dependent upon both the body radius R(y) and the integral of the function F(y) in the near field, whereas Whitham's characteristics show no such dependence. This is the basis of the improved theory discussed in this paper.

In order to determine whether or not the improved theory gives better results in the near field of a body of revolution at high Mach numbers than Whitham's theory, the wind tunnel data obtained in an earlier investigation (see capsule summary G-54) is used. Comparisons are made between the improved method, Whitham's theory, and wind tunnel results for four bodies of revolution - three closed-nose bodies and one ducted body. At Mach numbers of 2.96, 3.83, and 4.63 and ratios of radial distance to body length of 1.0, 2.0, and 5.0, the results showed that the improved method did reasonably well in predicting flow-field pressure signatures and represents a definite improvement over Whitham's near-field theory.

The fact that Whitham's near-field theory becomes increasingly inaccurate at Mach numbers above about 3.0 had been demonstrated in investigations by Hicks, et al. (see capsule summary G-33), Miller, et al. (see capsule summary G-53), and Shrout, et al. (see capsule summary G-54). Also, in an earlier paper Woodward (see capsule summary G-68) presented an improved near-field-high-Mach-number method which was based upon representing the aircraft configuration by various types of singularities rather

than by an equivalent body of revolution. However, the method of the present paper is less complex (although it is more complex than Whitham's method) and appears to give satisfactory results.

G-82

STUDIES ON SONIC BOOM AT HIGH MACH NUMBERS
Y. S. Pan and M. J. Varner
AIAA Paper No. 72-652, Presented at AIAA 5th Fluid and Plasma Dynamics Conference, Boston, Massachusetts, June 26-28, 1972

In this paper preliminary theoretical studies of the flow fields surrounding slender bodies at high supersonic and hypersonic Mach numbers are presented. For a sharp-nosed slender body in the high supersonic flow, the rotational effect of the flow field behind the moderate strength, attached leading shock wave is taken into account. The study is based on the concept of the shock-expansion method and is carried out using a quasi-linear approach. By comparing the formulations of the present study with those of Whitham's near-field theory (see capsule summary G-3), it is shown that the rotational effect represented by the entropy increase across the leading shock wave has a cumulative effect and a local effect on the flow field. This rotational effect is diminished for small flow deflections and at low supersonic Mach numbers.

The far-field flow patterns for a blunt-nosed body at hypersonic speeds are obtained by using the hypersonic equivalence principle and the existing near-field cylindrical wave solution. This theory was developed in an earlier paper by Pan and Sotomayer (see capsule summary G-71). The reader is referred to the capsule summary of that paper for details of this theory.

In a previous paper (see capsule summary G-81) Mack developed an improved method (as compared to Whitham's theory) for calculating the supersonic pressure fields of bodies of revolution. Although that method does not account for nonlinear effects as adequately as the method of the present paper, it is much simpler and appears to give satisfactory results for slender bodies of revolution.

G-83

THE BEHAVIOR OF SUPERSONIC FLOW PAST A BODY OF REVOLUTION, FAR FROM THE AXIS
G. B. Whitham
Proceedings of the Royal Society Series A, Vol. 201, 1950, pp. 89-109

In this paper a solution is obtained to the exact equations of motion for the supersonic flow past a body of revolution. The solution derived is valid only at large distances from the body axis. The solution is found as a series in descending powers of r (radial distance from body axis), and it is shown that, for the case of a slender body when the disturbance can be assumed to be small and hence certain terms neglected, the solution has the same form as the expansion of the linearized one except that the approximate characteristic variable $x - r\sqrt{(M^2 - 1)}$ is replaced therein by the exact one $y\,(x,r)$ such that y = constant is an exact characteristic curve. Hence it is deduced that the only failure of linearized theory at large distances is that the characteristics in it are incorrect. The only real use made of this fact, however, is that, by comparison the arbitrary function and constants appearing in the general theory are obtained in terms of the body shape. It is not until a later paper by Whitham (see capsule summary G-3) that the full potential of this finding is exploited by making the starting point of the theory the fundamental hypothesis that linearized theory gives a valid first approximation to the flow everywhere provided that in it the approximate characteristics are replaced by the exact ones. The significance of the present paper is that it layed the groundwork for Whitham's later paper.

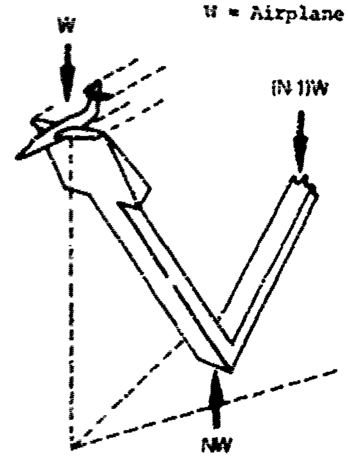
G-84

THE RELATION BETWEEN MINIMIZING DRAG AND NOISE AT SUPERSONIC SPEEDS
Adolf Busemann
Proceedings of the Conference on High-Speed Aerodynamics, Polytechnic Institute of Brooklyn, January 20-22, 1955, pp. 134-144

This paper discusses the far-field overpressures resulting from the lift and volume effects of a body in supersonic flight and the relation between minimizing the wave drag of a body and minimizing the sonic boom intensity. For a summary of the discussion of the latter topic see capsule summary M-1.

Equations are presented for calculating the shock strength in the far-field for an axial symmetric cone and for a lifting delta wing using linear theory. The transfer of lift from the airplane to the ground is discussed. The figure below, which was taken from this paper, illustrates Busemann's concept of the "lifting crowbar" which accomplishes this transfer of lift. The crowbar is a modified version of the lifting hyperbola by which the airplane weight is actually transferred to the ground.

N = Reflection factor
W = Airplane weight



Lifting Crowbar

This paper was the first to discuss the effects of lift on sonic boom and the transfer of airplane weight to the ground.

3.0 PROPAGATION

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P-1
SOUND WAVES IN THE ATMOSPHERE
E. A. Milne
Philosophical Magazine, S.6, Vol. 42., No. 247, July 1921, pp. 96-114

The equations of propagation of sound waves are derived in this paper for a medium in which the velocity of the medium and the speed of sound vary from point to point. These equations are in two sets, one expressing the convection at each point and the other the refraction. The derivation is limit[ed to] steady motion of the medium.

The derivation is based upon the following hypothesis: "The motion of a wave front is the same as if at each moment each point of it were moving with a velocity compounded of (1) the velocity of sound at the point considered, taken in the direction of the normal to the wave-front at this point, drawn in the direction in which the wave-front is progressing; (2) the velocity of the medium at the point."

This principle allows the successive positions of the wave-front to be determined if the motion of the medium and the speed of sound at each point is known. The curve whose tangent at each point is in the direction of the resultant velocity taken at the instant when the wave-front passes through the point is defined as a "sound ray." Equations are then derived, using a straightforward application of the above principle, for the complete sound ray passing through a given point and the partial differential equation satisfied by a family of surfaces successively occupied by a given wave-front. The equations for the sound ray are then simplified to the case of a point source in a stratified atmosphere for which the vertical component of velocity can be neglected.

For this stratified atmosphere the general expression of the law of refraction (Snell's law) is obtained:

$$a\sec\theta - a_o\sec\theta_o = u_o - u$$

where a = speed of sound; zero subscript denotes initial value; u = horizontal component of wind velocity in direction of given sound ray; θ = angle wave-front normal makes with horizontal.

It is also shown that the azimuthal angle of the wave-front normal along a particular ray remains constant.

This was the first generalized treatment of sound propagation in three dimensions. The two results given above for a stratified atmosphere were very significant developments in the theory of sound propagation.

P-2
A DETERMINATION OF THE WAVE FORMS AND LAWS OF PROPAGATION AND DISSIPATION OF BALLISTIC SHOCK WAVES
Jesse W. M. DuMond, E. Richard Cohen, W. K. H. Panofsky, and Edward Deeds
The Journal of the Acoustical Society of America, Vol. 18, No. 1, July, 1946, pp. 97-118

Both theory and experiment are used in this investigation to determine the laws which govern the propagation and dissipation of ballistic shock waves. Ballistic tests using bullets of various calibers are used to obtain experimental data. A theory is then developed, which is based mainly on conservation of energy, which supports the measured data.

The bullets tested were of the following calibers; 0.30, 0.50, 20mm, and 40mm. The peak amplitudes, wave lengths, and complete pressure signatures of the shock waves of each of these bullets were then recorded using microphones and oscilloscopes. The same general wave form was found to characterize the ballistic shock waves from all the calibers studied. This consists of a sharp rise in pressure followed by a nearly linear decline to a value about as far below atmospheric as the original rise and then a very sudden return to atmospheric pressure. This type of wave is referred to as an "N-wave." The measurements showed the peak amplitude of these shock waves to depend on miss distance, d, according to the law

amplitude = K/d^n; K = a constant depending on caliber, $3/4 < n < 1$.

The exponent n appeared to have about the value 3/4 for the three smaller calibers studied but for 40-mm bullets n was closer to one (about 0.9 ± 0.1). The statistical fluctuations in the amplitude measurements with microphones made it difficult by such means to determine n very precisely.

The measurements also showed the wavelength to be proportional to the fourth root of the miss distance. The wavelength was found to increase with increasing caliber.
A theory is then developed which is consistent with the field results. Instead of solving the wave propagation equations in three dimensions, the approximate method of computing the dependence of amplitude on miss-distance by using the principle of conservation of the wave energy (taking into account the rate at which it is degraded into heat) is used. The average energy density in the volume of revolution between the front and rear shock waves is assumed to diminish due to three reasons, the first two being merely geometrical increases in the volume containing the energy and the third being the dissipation into heat. The geometrical changes are the increase in the wavelength of the shock.

The Rankine-Hugoniot relations are derived from the laws of conservation of mass, momentum, and energy. These relations are then simplified to the case of weak shock waves. Using these relations, the thermal losses resulting from the irreversible changes of state occurring at the shocks are derived. It is also shown that the dissipation in the form of kinetic energy is of higher order than the thermal losses and can thus be neglected. The rate of dissipation into heat is also computed by an alternate hydrodynamic method and the results agree with those of the previous derivation.

The equation giving the rate of dissipation of

shock energy into heat, together with the propagation speeds of the front and rear shocks, is used to determine the rate of change of energy in the volume of revolution contained between the two shocks. The amplitude of the shock waves is then taken to be proportional to the square root of the energy density. The results show that, for sufficiently large miss distances (y greater than about 1,000 projectile diameters)

$$\frac{\Delta P}{P_o} = (\text{const.})y^{-3/4} \quad \text{and} \quad L = (\text{const.})y^{1/4}$$

where ΔP = bow shock overpressure, P_o = ambient pressure, L = wavelength, and y = miss distance.

These equations are in good agreement with the experimental results, except that in the equation for the amplitude of the shock wave the exponent of the miss distance is a little too small for the 40-mm results. It is hypothesized that this may be interpreted as meaning that for this large caliber the asymptotic rate of decay is not attained until greater miss distances than those observed.

The results found here agree with the later results of Whitham (see capsule summary G-3), which show the pressure amplitude to be inversely proportional to the three-fourths power of the miss distance and the wavelength proportional to the fourth root of the miss distance.

This is a very significant paper in sonic boom propagation theory. It was the first to correctly predict the decay rate of the bow shock overpressure and the rate of increase of wavelength, and to verify these findings experimentally. The physical ideas behind the mathematical derivations are explained very clearly, making this a very readable paper.

P-3
THE PROPAGATION OF SOUND IN AN INHOMOGENEOUS AND MOVING MEDIUM I
D. Blokhintzev
The Journal of the Acoustical Society of America, Vol. 18, No. 2, October, 1946, pp. 322-334

The wave equations for the propagation of sound in an inhomogeneous and moving medium are derived in this paper. Special cases are also considered, and a generalization of Huygens' principle is given for a moving medium. The general equations of acoustics are dealt with in the approximation of geometrical acoustics.

The equations for the propagation of sound are arrived at by proceeding from the general hydrodynamical equations of a compressible fluid disregarding only the viscosity and the heat conduction of the medium. The velocity, density, pressure and entropy are all assumed to undergo a small perturbation due to the passage of a sound wave. Expressions for these perturbed quantities are substituted into the conservation equations of mass, momentum, energy, and the equation of state, and only first order terms are retained. This results in a set of four equations for the velocity, density, pressure, and entropy perturbations. These are the principal equations of the acoustics of an inhomogeneous and moving medium. The special case of a medium whose entropy is constant is then considered.

The equations of geometrical acoustics are deduced from the four principal equations by assuming that the state of the medium varies little along a wavelength of sound. The resulting equations show the phase velocity of a sound wave to be given by

$$V_f = c + v_n$$

where V_f = phase velocity
c = adiabatic speed of sound = $(\partial p/\partial \rho)_s^{1/2}$
v_n = projection of velocity of flow on direction of normal to surface of constant phase
p = pressure, ρ = density, and s = entropy.

This is an important equation in describing the geometry of the sound field. It is essential, however, not merely to find the geometry of the sound field, but to compute quantities that describe the intensity of the sound. With this purpose in mind, an invariant quantity characterizing the energy density in a ray tube is derived. A ray tube is defined as a surface formed by rays (i.e., by lines along which the velocity V_s is directed where $V_s = \bar{C}\cdot\bar{n}+v$, where $\bar{n}$ is the normal to the wave-front and v is the wind velocity). This invariant quantity is derived from the principle of conservation of the average density of sound energy and is given by:

$$\frac{\pi^2 \cdot V_s \cdot \zeta}{\rho q c^2} = \text{const}$$

where ζ = cross-sectional area of ray tube
ρ = density
π = pressure perturbation = P - p
P = ambient pressure
p = local pressure
$q = c_o - v \cdot \nabla\theta$; v = velocity of medium; c_o = speed of sound in stationary medium; and θ = phase constant.

This quantity later came to be known as the "Blokhintzev invariant." It was used by Hayes in NASA CR-1299 (see capsule summary P-98).

In the last section of the paper the generalization of the principal equations for sea water is carried out.

This paper differs from Milne's (see capsule summary P-1) in that Milne deals chiefly with the description of the sound ray paths, while this paper considers both the sound ray path and the variation of physical quantities along the sound ray.

This paper is fundamental to the theory of sonic boom propagation in a nonuniform stratified medium.

P-4
THE PROPAGATION OF SOUND IN AN INHOMOGENEOUS AND MOVING MEDIUM II
D. Blokhintzev
The Journal of the Acoustical Society of America, Vol. 18, No. 2, October, 1946, pp. 329-334

In this paper two applications of the theory developed by Blokhintzev in Part I (see capsule summary P-3) are presented. These two applications are the propagation of sound in a turbulent medium and the propagation of sound through a shock wave.

With regard to the first application, it is concluded that the influence of turbulent flow on a sound wave should consist in a scattering of the sound. An expression for the magnitude of this scattering is derived using the theory previously developed by Blokhintzev.

When the general equations of Part I are applied to the passage of a sound wave through a shock wave it is found that there is no reflected wave; there are, however, two transmitted waves. The first, an acoustic wave, practically coincides with the incident wave for shocks having small pressure jumps so that sound passes through the front of the shock wave with very little perturbation. In the case of large pressure jumps, the pressure in the transmitted wave may be considerably greater than the pressure in the incident wave. Under all conditions the second transmitted wave, which is an entropy wave, is accompanied by variations in the density of the medium (and the temperature). The pressure perturbation due to this wave is always zero.

P-5

SOME ASPECTS OF NOISE FROM SUPERSONIC AIRCRAFT

G. M. Lilley, R. Westley, A. H. Yates, and J. R. Busing

Journal of the Royal Aeronautical Society, Vol. 57, June 1953, pp. 396-414

This paper was written at the time when the exact cause of the sonic boom of an aircraft which accelerated through the speed of sound in a dive was still being debated. It is demonstrated in this paper that the explanation of the boom lies in an understanding of the shock wave pattern around the aircraft.

The Mach wave patterns formed by an accelerating source are considered and it is shown that in unsteady supersonic motion the envelopes of the "pulse waves" form Mach waves of concave and convex curvature divided by cusps. The location of the wave envelope and cusps is then discussed.

Previous results concerning the shock wave formation around isolated two dimensional and axisymmetric bodies of revolution are discussed (see capsule summary G-3, for example), and the changes that occur in the system of shock waves around such bodies during accelerated flight are investigated. The main concern is with acceleration through the critical Mach number to a just slightly supersonic Mach number and then deceleration back through the critical Mach number. The manner in which the shock waves form, coalesce, and dissipate during such a maneuver is discussed in depth. Brief results of experiments in a hydraulic analogy channel are presented which qualitatively substantiate the predicted shock patterns. Several examples of the application of the theory to sonic boom predictions for specific flight conditions are then presented.

This paper was one of the first to predict the formation of cusps in the shock wave due to accelerated flight. It also was one of the first to correctly explain the early sonic booms resulting from aircraft which reached supersonic speeds during dives.

P-6

ON THE ENERGY SCATTERED FROM THE INTERACTION OF TURBULENCE WITH SOUND OR SHOCK WAVES

M. J. Lighthill

Proceedings Cambridge Phil. Soc., 49, 1953, pp. 531-551

An investigation of the energy scattered when a sound wave passes through turbulent fluid flow is presented in this paper. The energy scattered per unit time from unit volume of turbulence is estimated as

$$\frac{8\pi^2 L_1}{\Lambda^2} \; \frac{\overline{v'^2_1}}{a^2}$$

where I is the intensity and Λ the wave length of the incident sound, $\overline{v'^2_1}$ is the mean square velocity and L, the macro-scale (size of largest turbulent eddies) of the turbulence in the direction of the incident sound, and a is the speed of sound. This formula does not assume any particular kind of turbulence, but does assume that Λ/L_1 is less than about 1. For turbulence which is isotropic and homogeneous, the energy scattered, and its directional distribution, are obtained for arbitrary values of Λ/L_1. It is predicted that components of the turbulence with wave-number K will scatter sound of wave-number K at an angle $2 \sin^{-1} (K/2K)$. The statistics of multiple scatterings is considered and it is predicted that sound of wave-length less than the micro-scale λ of the turbulence will become uniform (random) in its directional distribution in a distance of approximately $\lambda a^2/\overline{v'^2_1}$.

The theory is then extended to the case of an incident acoustic pulse. However, this extended theory cannot be applied directly to the case of a shock wave, for which it would predict infinite scattered energy. This is due to the perfect resonance between successive rays emitted forwards which would occur if the shock wave were propagated at the speed of sound. By taking into account the true speed of the shock wave (subsonic relative to the fluid behind it) the theory is improved to give a finite value for the total energy scattered. However, the greater part of this energy catches up with the shock wave and is mostly reabsorbed by it, and only the remainder is freely scattered, behind the shock wave, as sound.

In a later paper (see capsule summary P-15) Batchelor treats the same subject but uses a different approach.

P-7

METEOROLOGY DIRECTS WHERE BLAST WILL STRIKE

Everett F. Cox, H. J. Plagge, and J. W. Reed

Bulletin of the American Meteorological Society, Vol. 35, No. 3, March, 1954, pp. 95-103

An approximation to the theory of geometric acoustics is used to forecast where the shock due to an explosion will strike the earth. In this method it is assumed that there are no vertical winds and that the wind and temperature structure is exactly the same over the entire region of interest as it is over the shot site.

The refraction law (i.e., Snell's law) for an atmosphere having only horizontal winds is assumed to be:

$$c + u_i \cos\theta = A_i \cos\theta$$

In this case θ is the inclination of the sound ray from the horizontal. In order for this equation to be strictly true, θ would be the inclination angle of the wave front normal from the horizontal (see capsule summary P-1). However, the present approximation is valid for the horizontal propagation of the ground level disturbances with which the present paper is concerned. The other variables in this equation represent the following:

u_i is the component of wind velocity in the direction under consideration: and A_i, invariant for a given ray, is the horizontal component of the velocity of the wave front. In this paper the following additional approximation to the refraction equation is used:

$$A_i \cos\theta \approx V_i = c + u_i$$

It is important to note that this approximation, which sets the component of the wind velocity along the ray equal to the horizontal component of wind velocity in the given direction, is valid only for ground level disturbances. It would not, therefore, be valid for predicting the propagation of sound waves or sonic booms from an airplane at high altitude.

In conjunction with this equation a table is constructed listing c and u_i at selected altitudes. These are added at each altitude to give V_i. When the value of V_i at the earth's surface exceeds its values at all higher altitudes, no shock will strike the ground in that direction from a surface shot. If the value of V_i at any altitude exceeds that at the ground, the shock will strike the ground in that direction.

An expression for the distance from the explosion at which the shock will strike the ground in a given direction is then derived for various example atmospheres. This expression is used to investigate the focusing of sound.

It was pointed out that in this paper the component of the wind velocity along the ray is set equal to the horizontal component of wind velocity in the given direction. This is a valid approximation for the case of horizontal propagation of ground level disturbances. But in a later paper (see capsule summary P-26) Reed and Adams use the same approximation to calculate the propagation of sonic boom shock waves from a body of revolution in supersonic flight at high altitudes. As a result, the results they obtain are incorrect.

This paper, although not directly related to the sonic boom, does provide an interesting example of the application of geometric acoustics to shock wave propagation.

P-8

GEOMETRICAL ACOUSTICS. I. THE THEORY OF WEAK SHOCK WAVES

Joseph B. Keller

Journal of Applied Physics, Vol. 25, No. 8, August, 1954, pp. 938-947

A complete derivation of geometrical acoustics is given in this paper. The derivation begins with the fundamental equations of continuum mechanics: the conservation equations of mass, energy, linear momentum, and angular momentum, plus the first and second laws of thermodynamics. From these equations the discontinuity conditions for curved discontinuities in any continuous medium are derived. It is then shown that only three types of discontinuities are possible - shocks, contact surfaces, and phase-change fronts. The acoustic equations are found by differentiating the discontinuity conditions with respect to a parameter n, upon which the set of solutions of the equations of continuum mechanics are assumed to depend. This results in seven variational equations for the acoustic density, entropy, velocity, etc., which are defined as the variations of the corresponding undifferentiated quantities. The acoustic discontinuity conditions are obtained by differentiating the discontinuity conditions of continuum mechanics with respect to n.

The acoustic shock surfaces or wave fronts are defined by W = constant. A first order partial differential equation is derived for W from the acoustic discontinuity conditions. This equation is:

$$(u_j W_{x_j} - 1)^2 = c^2 W_{x_j}^{\ 2}$$

where u_j = j^{th} component of particle velocity, the x subscript denotes partial differentiation, j takes on the values 1, 2, 3, and the summation convention is understood. Wave normals are then defined by $P_i = W_{x_i}$.

The Hamiltonian function, which is defined by

$$H(x_i, P_i) = c^2 P_j^2 - (1 - u_j P_j)^2,$$

is used to introduce certain curves $x_i(\sigma)$ called rays. These rays are given by:

$$\frac{dx_i}{d\sigma} = \lambda H_{P_i} = 2\lambda \left[c^2 P_i + u_i c \, (P_j^{\ 2})^{1/2} \right]$$

where λ is an arbitrary nonzero factor,
c = speed of sound and i = 1, 2, 3

By means of the rays, solutions can be constructed for the wave-front equation corresponding to any given initial data.

The variation in shock strength along a ray is derived by considering the acoustic equations

for a perfect, nonconducting fluid. The resulting equation is:

$$\frac{(\Delta\dot{P})^2}{\rho c} = \frac{1}{K}\left|\frac{(\Delta\dot{P})}{\rho c}\right|^2_{\sigma_0}$$

where ρ = density
$\dot{P} = \partial P/\partial n$ and P = pressure
and k is the expansion ratio along the ray, which is defined as the limit of the ratio of the normal cross-sectional area of a tube of rays at σ divided by the corresponding area at σ_0, as the area tends to zero. The tube of rays contains the ray in question and converges to it.

Once $\Delta\dot{P}$ is known, $\Delta\hat{\rho}$ and Δu_i can be computed from the acoustic discontinuity conditions. Here $\hat{\rho}$ is the acoustic density, and u_i is the acoustic velocity.

The reflection and transmission coefficients for an acoustic shock at a contact surface are then obtained, and the expansion ratio for the case of straight rays is computed. This ratio is given by:

$$k^{-1} = \frac{R_1R_2}{(R_1+z)\ (R_2+z)}$$

where R_1, R_2 are the principal radii of curvature of a surface at a point, and R_1+z and R_2+z are the corresponding radii of a parallel surface at a point a distance z away on the same ray. From this equation it can be seen that k^{-1} becomes infinite at two points $z = -R_1, -R_2$ called conjugate points, on each ray. The locus of these points for a given family of wave fronts is called a caustic surface and usually has two branches. A point at which the two branches of the caustic surface touch is called a focus. The acoustic shock strength becomes infinite on a caustic, since k^{-1} becomes infinite there.

An example is then given of the application of geometric acoustics to a shock tube.

Although this paper deals essentially with the same subject treated by Blokhintzev (see capsule summary P-2), that of geometric acoustics, the approach used in deriving the various equations and also the specific equations that are derived by Keller differ significantly from those of Blokhintzev. This paper is more specialized than that of Blokhintzev because it deals primarily with propagation of shock discontinuities.

P-9
AN ESTIMATION OF THE OCCURRENCE AND INTENSITY OF SONIC BANGS
C.H.E. Warren
Royal Aircraft Establishment, Technical Note No.: Aero. 2334, September 1954.

This paper is an early investigation into the occurrence and intensity of sonic booms. It is shown that an observer will experience a sonic boom if an aircraft has flown so that the component of its velocity in his direction is sonic. The intensity of a boom depends primarily upon the altitude of the aircraft at the time that its velocity toward an observer is sonic. Mach number has a relatively small effect, as also has the size of the aircraft, an increase in aircraft weight by a factor of ten increasing the pressure intensity of the boom by a factor of only about two. The affected area is shown to have appreciable width, although for flight at low altitudes the width will depend very much upon the effects of refraction and scattering of the shock waves by ground obstacles, etc. It is shown that sonic booms of a very increased intensity are quite possible, but will be experienced over a relatively small area.

Finally, refraction is shown to have an important bearing on the occurrence of booms. The subject of complete cut-off is touched upon. It is concluded that the importance of refraction, implying a close dependence of sonic boom phenomena on the atmospheric conditions prevailing, and the importance of precise flight path of the aircraft and the location of the observer, all tend to make sonic booms quantitatively unpredictable in practice.

This is one of the earliest papers dealing with the sonic booms caused by aircraft in steady, level flight. Several of the conclusions, such as the one concerning the effect of aircraft weight, were later shown to be somewhat in error.

P-10
GEOMETRIC THEORY OF SOUND PROPAGATION IN THE ATMOSPHERE
G.V. Groves
Journal of Atmospheric and Terrestrial Physics, Vol. 7, 1955, pp. 113-127.

The object of this paper is to obtain a general solution for the propagation of sound rays and wave fronts in a moving inhomogeneous atmosphere in terms of the velocity of sound and wind fields.

The equation of the wave front at time t is given by $\bar{r} = \bar{r}\ (\alpha,\ \beta,\ t)$ with reference to a fixed origin, O. The values (α,β) are taken as parametric coordinates of the points of the surface. The unit normal at the point (α,β) is given by $\bar{n} = \bar{n}\ (\alpha,\ \beta,\ t)$. Two first order differential equations are then derived for $\bar{n}$ and $\bar{r}$ beginning with the condition defining the propagation of a wave front in geometrical acoustics, which was derived by Blokhintzev and is given by

$$|\nabla\theta| = c_o/\ (c+\bar{W}\cdot\bar{n})$$

where c_o is a reference velocity
$\bar{W}$=velocity of medium
c = speed of sound
$\theta(\bar{r}) = c_o\ (t-\psi_o/\omega)$
ψ_o = phase of given wave front
ω = frequency

The two differential equations, which could be solved simultaneously for $\bar{r}\ (\alpha,\ \beta,\ t)$ and $\bar{n}\ (\alpha,\ \beta,\ t)$ in terms of the initial form of the wave front, are:

$$\bar{r}_t = \bar{W}\ (\bar{r},\ t) + c\ (\bar{r},\ t)\ \bar{n}$$

$$\bar{n}_t = (\bar{n}\cdot\nabla q)\ \bar{n} - \nabla q$$

where $q\bar{n}$ is the velocity of propagation of the wave front in space. However, instead of solving these equations, a transformation is made by expressing $\bar{n}$ in terms of the trace velocities of

the wave front. The trace velocities v_x, v_y, and v_z are defined as follows: if the tangent plane at the point (α, β) of the wave front at time t moves instantaneously in the direction of the normal, the points x, y, z where this plane cuts O_x, O_y, and O_z have velocities v_x, v_y, v_z, along O_x, O_y, O_z, respectively. The transformation results in the following equation, which replaces the second one given above:

$$\bar{h}_t + (|\bar{h}|c' + \bar{h} \cdot \bar{W}')\,\bar{h} + \nabla(|\bar{h}|c + \bar{h} \cdot \bar{W}) = 0$$

where the prime denotes differentiation with respect to t and

$$\bar{h}\,(\alpha, \beta, t) = (1/v_x\,(\alpha, \beta, t),\ 1/v_y\,(\alpha, \beta, t),\ 1/v_z\,(\alpha, \beta, t))$$

This equation is then solved for the case where the sound speed and wind velocity are functions of altitude only to get v_x, v_y, and v_z as functions of the sound speed, wind velocity, and α, β. It is found that v_x and v_y are independent of t and can be written as

$$v_x = a\,(\alpha, \beta),\quad v_y = b\,(\alpha, \beta).$$

This means that along any ray (α, β), v_x and v_y remain constant. A new parametric system of coordinates (a, b) defined by the transformation $a = a(\alpha, \beta)$, $b = b(\alpha, \beta)$. Using this solution and these new coordinates, the law of refraction is found to be:

$$[c(z) + \lambda u(z) + \mu v(z) + \nu w(z)]/\lambda = a$$

$$[c(z) + \lambda u(z) + \mu v(z) + \nu w(z)]/\mu = b$$

where u, v, w are the components of the wind velocity vector and λ, μ, ν are the direction cosines of the wave front normal. For fixed values of a and b, these relations give the direction cosines of the wave front normal along the ray (a, b). These equations are the generalized form of Snell's law.

The conditions for total reflection of a sound ray, and the equations for the wave front at any time are then found, and, as an example, the theory is applied to a simple velocity of sound vs. height relation.

Assumptions that had been made in previous treatments of this subject such as the vertical component of the wind being zero, the ray paths lying in vertical planes, and the wave front being planar were found to be unnecessary in this investigation. As a result the refraction equations are more general than any derived previously.

P-11 ·

SUPERSONIC BANGS--PART I

P. Sambasiva Rao

Aeronautical Quarterly, Vol. 7, Feb., 1956, pp. 21-44

The purpose of this paper is to extend Whitham's theory to the case of accelerated motion. The theory is limited to the bow shock of a slender axisymmetric body in a uniform atmosphere.

The theory is obtained by a suitable modification of the linear solution to the problem. Rather than dealing immediately with the full linear solution, which is too complicated for the modification to be applied as it stands, the approximate form which it takes near the wave fronts (which are ultimately replaced by shocks) is considered in detail first. Since the behavior near the wave front is precisely the subject of geometrical acoustics (see capsule summaries P-3, P-8, P-10), this theory is used to determine the geometry of the wave fronts and the approximate variation of flow quantities immediately behind the wave front. However, the solution given by geometric acoustics is not a valid linear solution as the distance from the body becomes large. This is because, as the shock propagates out, the wavelets behind the shock are continually being fed into the shock. Thus at large distances from the body it is necessary to use the full linear solution. This results in a relation between the velocity potential of the flow, the body geometry, and the acceleration of the body.

The linear theory solution is then improved, using Whitham's technique (see capsule summary G-3). This involves correcting the linear theory characteristics to account for cumulative nonlinear effects, but retaining the value given by linear theory for the physical quantities along each characteristic. The "angle property" (see capsule summary G-3) is used to determine the shock location.

The main result is the expression for the bow shock overpressure of an accelerating slender axisymmetric body:

$$\frac{P-P_o}{P_o} = \left(\frac{1}{2}a_o\right)^{1/2} \gamma M^3 F(n) \left|a_o M\beta^2 s - M' s^2\right|^{-1/2}$$

where P = local pressure
P_o = undisturbed pressure
a_o = ambient speed of sound
M = Mach number
$M' = U'(\tau_o)/a_o$
U = speed of the body
τ_o = time when nose of body crosses the ray through the point (x,r)
x,r are distances of a point along and perpendicular to the flight path.
$\beta = \sqrt{M^2-1}$
s = distance of any point along the ray
F(n) = Whitham F-function (see capsule summary G-3)

This equation reduces to the result for the steady problem (Whitham) when the acceleration is set equal to zero.

Numerical computations based on the overpressure equation given above are then given to show how the shock strength varies with distance and acceleration. Finally, a formula is derived for the decay at large distances of a shock detached from a decelerating body.

It is shown that the effect of acceleration is to increase the shock strength while that of deceleration is to decrease it. The modification of the shock strength due to acceleration is appreciable at large distances from the nose and at Mach numbers near unity. The theory is not valid near the cusp of the wave front, which results from accelerated motion.

In part II of this paper (see capsule summary P-12) the theory is extended to include curved flight paths.

This paper, due to its restrictive assumptions, (i.e., homogeneous atmosphere, front shock, simple bodies, etc.) can be used for qualitative results only. These are only valid far away from the caustics. The paper was significant, however, in isolating and defining the caustic mechanism due to accelerated flight.

P-12

SUPERSONIC BANGS--PART II

P. Sanbasiva Rao

Aeronautical Quarterly, Vol. 7, May 1956, pp. 135-155

The theory developed in Part I (see capsule summary P-11) is extended to include curved flight paths. The basic method is unchanged from that used in Part I. Acoustic theory provides a first rough approximation of the geometry of the shocks; the wave fronts are the linear approximations to the shocks. However, the linear theory does not give an accurate estimate of the shock strengths. To obtain an accurate evaluation of the shock strengths, certain nonlinearities must be incorporated. This involves the use of the correct propagation speed (equal to the local speed of sound relative to the fluid) for the individual sound waves. Then, since the waves move with different speeds, they pile up in compression regions to form shocks. Thus shocks are introduced as an essential part of the theory.

In applying these ideas, the geometrical acoustic approximation to the full linear theory is mainly used. In the theory of geometrical acoustics (see capsule summaries P-3, P-8, and P-10) the rays are defined as the orthogonal trajectories of the wave fronts. This theory provides an approximate determination of the amplitude of the disturbance as it moves along a narrow tube formed by neighboring rays (ray tube). As explained in capsule summary P-11, it is necessary to use the full linear theory at large distances from the body.

After modifying the results of linear theory, the resulting expression for the overpressure is:

$$\frac{P - P_o}{P_o} = \frac{M^{5/2}\ \gamma F(n)}{\left|2\ (M^2 - 1)\ S\ (1 - S/\lambda)\right|^{1/2}}$$

where P = local pressure; P_o = ambient pressure; M = Mach number; F(n) = Whitham F-function (see capsule summary G-3); S = distance along a ray from body; γ = ratio of specific heats in air;

$$\lambda = \frac{a_o^{\,2}\ (M^2 - 1)}{a_o^{\,2}\ (M^2 - 1)^{1/2}\ \ MK \cos\theta + (a_o/M)(dM/d\tau)_{\tau=\tau_o}}$$

a_o = ambient speed of sound; K is the curvature of the flight path; θ is the polar angle in a plane perpendicular to the flight path; $a_o\ dM/d\tau$ is the acceleration along the flight path; and τ is the time when a disturbance leaves the body; M_∞^2 K is the component of acceleration perpendicular to the flight path; and $S(1 - S/\lambda)$ is proportional to the cross-sectional area of a bundle of neighboring rays. It is important to notice that the function F(n) is exactly that used to describe the flow pattern for the same body moving uniformly.

The important parameter in this equation is the acceleration component along the ray. The only essential effect of the curvature of the path is the inclusion in this acceleration component of a term due to the transverse acceleration.

The strength of the bow shock is obtained and it is found that the effect of the curvature of the path is more pronounced at points on the inside of the curve, and in general it becomes greater as the distance from the body increases. A simple asymptotic formula is obtained which predicts the strength of the shock with an error of less than five percent at distances of the order of a hundred body lengths. Also, an estimate is obtained of the shock strength near a cusp by modifying the full linear theory.

The significance of this paper, along with Part I, is that it enables the sonic boom intensity to be calculated for any type of airplane motion, whereas Whitham's theory is valid only for steady level flight. However, as was pointed out in capsule summary P-11 the results are valid only for a restricted class of problems (i.e. homogeneous atmosphere, front shock, simple bodies, etc.)

P-13

SOUND PROPAGATION IN THE LOWER ATMOSPHERE

P. Rothwell

The Journal of the Acoustical Society of America, Vol. 28, No. 4, July 1956, pp. 656-665

This paper describes experiments conducted to compare observations of the range of audibility and descent angle from shell bursts at various heights up to 10,000 feet with calculations made from extensively measured temperatures and winds. It is stated that range of audibility does not provide a conclusive test of the validity of the assumptions made in calculating sound rays in the atmosphere, although the effects of refraction on the range of audibility may be significant. This is because the boundary ray which determines the range becomes horizontal at some point in its path. Small variations in sound speed at the height of this point produce large changes in range. The observed range of audibility also depends on a number of factors other than refraction, such as the sensitivity of the receiver and the background noise.

However, the descent angle can be measured anywhere within the range of audibility and is not unstable, except when approaching zero.

The fundamental equation used in the calculations is:

$$c \sec\theta + u = \Lambda$$

where c = speed of sound

u = component of wind velocity in direction of given sound ray

θ = inclination angle of sound ray below horizontal

Λ = constant for a given sound ray

This is the law of refraction derived by Rayleigh for an atmosphere in which both the speed of sound and the wind velocity are functions of height.

The results show that for stable atmospheric conditions there is satisfactory agreement between the calculated and measured results. Thus the significance of this paper is that it verified the theory of sound propagation in use at that time.

P-14
ON THE PROPAGATION OF WEAK SHOCK WAVES
G. B. Whitham,
Journal of Fluid Mechanics, Vol. I, Sept. 1956, pp. 290-318

In Whitham's most well-known paper (see capsule summary G-3) a method was derived for predicting the strength of the shocks in the steady supersonic flow past an axisymmetrical body. In the present paper the method developed for predicting the propagation of weak shock waves is extended to problems lacking such symmetry. The treatment is limited to a uniform atmosphere.

In formulating the basic ideas of the theory, the problem of a weak explosion is considered first. The following simplified model is used: A region of arbitrary shape, bounded by a surface S, contains gas, which is initially at rest, having a higher pressure than that of its surroundings. This gas is released suddenly at time t = 0. According to the theory of sound, the wavefront carrying the first disturbance outward from the explosion moves with the constant speed of sound in the undisturbed gas surrounding the explosion along the normals to the surface S. These normals, known as rays, are the orthogonal trajectories of the successive positions of the wavefront. The magnitude of the disturbance and the variation in the magnitude of the pressure jump at the wavefront as it moves out along a ray is correctly predicted by the theory of sound. However, the approximation of geometrical acoustics can be used near the head of the wave. The reason for this is that, in certain circumstances, the energy propagated down a ray tube is conserved; that is, reflection and diffraction of energy may be neglected. Therefore, letting A(S) be proportional to the cross sectional area of the ray tube at the distance S along the ray, the amplitude of the pressure disturbance varies like $A^{-1/2}(S)$ with distance S along the tube, since the flux of energy across any section of the ray tube is proportional to the square of the amplitude times the area. However, in reality, the wavefront is replaced by a shock wave, and the dissipation of energy by the shock cannot be neglected and neither can the related distortion of the wave profile behind the shock. Thus, even for weak shocks, the result that the shock strength varies with S like $A^{-1/2}(S)$ requires modification. This inaccuracy is not introduced by the approximations of geometrical acoustics, it is a failure of the linear theory of sound.

Even though its prediction of the shock strength is incorrect, geometrical acoustics still provides the key to the solution of these unsymmetrical shock problems. It is assumed that the propagation of the disturbances may be treated separately in each ray tube. This results in a two variable problem depending on time t and distance S. This problem can then be solved using the same methods used in developing the original theory for symmetric shocks. The other variables in the problem appear only in the function which specifies the initial wave profile for each tube and as parameters in the function A(S).

The improved theory treats any point of a shock as moving with the speed of sound appropriate to the shock at that point. Thus if the shock strength varies there will be a tendency for the true rays to curve away from the rays of linear theory. However, unless the shock strength varies rapidly, the effect of this curvature will be small. Thus the theory developed here neglects the deviation of the rays from their linear positions.

A general account is then given of the method for improving the linear theory of the propagation in the individual ray tubes. The required non-linear features are introduced by taking account of the progressive distortion of the wave profile due to the small variations in the propagation speeds of the individual wavelets of each wavefront. The dissipation of energy is incorporated by applying the Rankine-Hugoniot shock conditions.

The resulting expression for the pressure behind the shock for large S is given by:

$$\frac{P_1 - P_o}{P_c} \sim \left\{\frac{4\gamma a_o}{\gamma + 1} \int_0^{T_o} F(T')dT'\right\}^{1/2} \left\{\int_0^S \frac{dS}{\sqrt{A}}\right\}^{-1/2}$$

where P_1 = pressure behind shock

P_o = undisturbed pressure

a_o = ambient sound speed

T(S) = time at which the shock reaches the position S

F(T) determines detailed wave profile and depends on initial conditions in particular problem considered (see capsule summary G-3 for an example).

The remainder of the paper is devoted to applications of the theory in specific cases. These include the outward propagation of spherical shocks, an unsymmetrical explosion, a review of Rao's theory (see capsule summaries P-11 and P-12), the flow past a flat plate delta wing at small incidence to the stream with subsonic leading edges, and the problem of a thin wing having a finite curved leading edge. The last two examples are of the greatest interest, as far as sonic boom theory is concerned.

The treatment of the flow past a flat plate delta wing at incidence is of special significance in sonic boom theory because this was the first treatment of lift effects on the shock strength of a lifting body. The equation derived for the overpressure is

$$\frac{P - P_o}{P_o} = \frac{\gamma M^2 F(\tau)}{(2Br)^{1/2}}$$

where $B = \sqrt{M^2 - 1}$

r = radial distance from flight path

τ = const. defines corrected characteristics

$F(\tau) = q(\theta)\ 2^{-1/2}\ \tau^{1/2}$

$q(\theta)$ depends upon the shape of the wing and the magnitude of the lift and θ is measured from the plane of the wing.

To a first approximation, the flow is in meridian planes and θ plays the role of a parameter. This equation is the same as Whitham's general formula (see capsule summary G-3), the only difference being that the form of the F-function differs from that for a body of revolution.

In the application of the theory to the problem of a thin wing having a finite curved leading edge, it is found that in any given direction the shock from the leading edge ultimately decays exactly as for the bow shock on a body of revolution. The equivalent body of revolution for any direction is determined in terms of the thickness distribution of the wing and varies with the direction chosen. The wave drag on the wing is calculated from the rate of dissipation of energy by the shocks. The drag is found to be the mean of the drag on the equivalent bodies of revolution for the different directions.

This is a very significant paper in the development of sonic boom propagation theory because it gives the first treatment of shock waves from non-axisymmetrical configurations. Also, it gives the first treatment of shock wave propagation using the first modification to linear theory.

P-15

WAVE SCATTERING DUE TO TURBULENCE

G. K. Batchelor

Symposium on Naval Hydrodynamics, Sept. 24-28, 1956, Washington D.C.

Publication 515 National Academy of Sciences--National Research Council, 1957, pp. 409-430

The scattering of sound waves due to turbulence in a non-uniform medium is discussed in this paper. The starting point of the calculations is a linear modified wave equation. A solution is found for this equation which represents the passage of a sound wave through a region in which the random physical properties of the medium are known in a statistical sense. A perturbation procedure is used to obtain this solution. In obtaining this solution, it is assumed that the frequency of the incident sound wave is much higher than the fractional rates of change of the physical variables. This means that the dependence upon time plays only a minor role in the problem.

The scattering of the sound wave by turbulence is investigated first. An expression is derived for the mean intensity of the scattered wave, expressed as a fraction of the intensity of the incident wave, for points whose distance from the scattering volume V is large compared with the linear dimensions of V. The flux of energy in the scattered wave direction is also derived and is expressed in terms of a quantity called the "scattering cross-section." The fraction of the energy of the incident wave that is lost by scattering, per unit length travelled by the incident wave front, is also expressed in terms of the scattering cross-section. The discussion then turns to a consideration of the equations that describe the propagation of sound waves. Two cases are treated: first a medium of variable physical properties which is stationary except for the disturbance caused by the incident wave, and second a medium of uniform physical properties in turbulent motion.

For the case of a stationary non-uniform atmosphere, an expression is derived for the directional distribution of intensity of the scattered wave in terms of the distribution of density fluctuations of the medium. For the case of a uniform medium in turbulent motion, in which the only effect is that of turbulent fluctuations of velocity on the propagation of sound waves, an expression for the scattering cross-section is derived in terms of the distribution of turbulent velocity. In connection with this case it is found that the interaction between the sound and turbulence fields is weak, and that they perturb each other. This lack of coupling is basically a consequence of the big difference in the time scales on which changes take place in the two fields. Thus the perturbations in density, pressure, and velocity due to the incident sound wave are the same as in a stationary medium.

In an earlier paper (see capsule summary P-6) Lighthill treats basically the same subject using his theory of the generation of aerodynamic noise. However, Lighthill extends his theory to include the interaction of shock waves with turbulence, while Batchelor treats only the interaction of sound waves and turbulence. Both of these papers were valuable in forming a basis for the description of shockwave-turbulence interactions that lead to signature distortions.

This paper was later reprinted for an AIAA Sonic Boom Theory Seminar (see capsule summary P-93).

P-16

SOUND PROPAGATION IN AIR

Everett F. Cox

Handbuch der Physik, Vol. 48, Geophysik II, 1957, pp. 455-478

A summary of sound propagation theory is presented in this paper. The author begins at a very basic level by defining what is sound and what is its intensity at a point. Laplace's equation for the speed of sound is then discussed and the difference between macro- and micrometeorology is explained. In connection with this it is pointed out that sound, as a rapidly propagated phenomenon, is affected by the atmospheric inhomogeneities due to micrometeorology. Here macrometeorology refers to large-scale weather patterns, while micrometeorology refers to smaller scale phenomena such as turbulence.

In using the law of sound refraction, the same approximation is made as was made by Cox, Plagge, and Reed in a previous paper (see capsule summary P-7). This approximation sets the wind velocity in the direction of sound propagation equal to the horizontal wind at each altitude. The justification for this approximation is that the wind speed seldom exceeds ten or fifteen percent of sound speed, at least within the troposphere.

The resulting vector form of the refraction equation is

$$\bar{V} = \bar{X}\cos\theta$$

where $\bar{X}$, invariant for any selected sound ray, is the velocity of the intersection of the wave front with the horizontal. It is important to note that this approximation is not valid for the propagation of sound from an airplane.

Absorption, dispersion, and reflection are then discussed briefly before applying the theory of sound propagation to a few specific examples. In these examples, the effect of various atmospheric temperature profiles on the propagation of sound from an explosion is investigated. It is shown, for example, that when the sound velocity in some azimuthal direction increases uniformly with altitude, sound rays strike the ground at all points in that direction, all rays starting at sufficiently small angles with respect to the horizontal being refracted back to earth and then duplicating their path forms over and over again by reflection and refraction. When the speed of sound in a given direction is less at all higher altitudes than that on the ground, all of the sound rays are bent away from the ground and none hit the earth, except for cases of abnormal or anomalous propagation, which is the final topic. This subject deals with the refraction of sound rays by the upper atmosphere.

This paper is very similar to an earlier paper by Cox, Plagge, and Reed. The present paper, although having broader subject coverage, is still not applicable to the propagation of sonic booms from airplanes at high altitudes.

P-17
A NEW APPROACH TO THE PROBLEMS OF SHOCK DYNAMICS. PART I. TWO-DIMENSIONAL PROBLEMS
G. B. Whitham
Journal of Fluid Mech. Vol. 2, 1957, pp. 145-171

Two-dimensional problems of the diffraction and stability of shock waves are investigated in this paper. An approximate theory is used in which disturbances to the flow are treated as a wave propagation on the shocks. Changes in the slope and Mach number of the shock are carried by these waves. The wave propagation is governed by equations which are analogous to the non-linear equations for plane waves in gas dynamics. It is found that the propagation speed of the waves is an increasing function of Mach number. Thus, waves carrying an increase in Mach number will eventually become multi-valued and form what is ordinarily called a shock. This corresponds to the breaking of a compression wave into a shock in the ordinary plane wave case. A shock of this type moving on the shock is called a "shock-shock." The "shock-shock" is a discontinuity in Mach number and shock slope. It must be fitted in to satisfy the appropriate relations between these discontinuities and its speed.

The set of curves formed by the successive positions of a curved shock as it moves forward through a uniform medium and the orthogonal trajectories of this set of curves are used as the basis for orthogonal coordinates in the plane. Coordinates (α,β) are introduced such that the rays are β = constant and the shock positions are α = constant. The assumption is made that the propagation of the shock between any two neighboring rays can be treated as if the rays were solid walls. Two relations are found between M and A where M is the Mach number of the shock at (α,β) and $A(\alpha,\beta)d\beta$ is the distance between the rays β and $\beta + d\beta$. This results in an explicit equation for the Mach number of the shock as a function of (α,β) and, from this function, the shock position can be determined for all times.

The method is kept simple by avoiding a detailed discussion of the flow behind the shock through the assumption that A is a function of M. Thus the theory can only be applied to certain types of problems. One example of a case for which the theory would not apply is in explosion problems in which the propagation of disturbances originating far behind the shock must be considered. However, for the diffraction of a uniform plane shock by an obstacle, the disturbance originates at the shock and thus it is more plausible to limit discussion to the neighborhood of the shock. Also, stability is largely a matter of local adjustment of the flow near the shock and can be included in the applications.

The examples treated include the diffraction of a shock moving along a non-uniform wall, diffraction by a wedge, diffraction by a small corner, the stability of plane shocks, and the stability of cylindrical shocks.

In the case of diffraction by a wall, if the wall always turns away from the flow region, an expansive wave originating at the wall moves out along the shock. If the wall turns toward the flow, a compressive wave is sent out along the shock. Eventually this wave becomes multivalued and a shock-shock is formed.

For diffraction by a wedge, the solution is a shock-shock separating two uniform regions--the familiar Mach reflection. The present theory does not alleviate the difficulties in the conventional solution for conditions at a three shock intersection. It does, however, provide a method for treating variations in the three shock configuration which would be caused by further curvature of the wall of the wedge, for example.

The case of a small corner allows a check to be made with the results of previous theories. The comparison shows that the approximate method developed here is most suitable for strong shocks with Mach number greater than about 2, and must be used with care for weaker ones. The predicted changes in Mach number are in good agreement for all strengths, but for very weak shocks the geometry of the disturbed flow is not given accurately.

The reason that the theory developed here is more suitable for strong shocks is that this theory cannot avoid concentrating the change in Mach number over a relatively small part of the shock. For the stronger shocks, the results of previous theories show that this concentration is correct. However, for weak shocks, the results of previous work show that the disturbance should be spread out over the entire part of that shock that is within the sonic circle. A compromise is made in the present theory in that the disturbance is concentrated halfway to the sonic circle.

The theory is then used to demonstrate that plane shocks are very stable. It is shown that as the concave curvature of a shock increases, its strength increases, which results in a tendency for the curvature to decrease. It is hypothesized that this would preclude focusing of plane waves. It is also shown that cylindrical shocks are unstable.

Part II of this paper (see capsule summary P-22) extends this theory to three dimensional problems.

The question of the validity of this theory for Mach numbers less than 2 severely restricts its utility in sonic boom applications.

P-18

THE SHOCK PATTERN OF A WING-BODY COMBINATION, FAR FROM THE FLIGHT PATH

F. Walkden

Aeronautical Quarterly, Vol. IX, Part II, May 1958, pp. 164-194

This paper deals, for the most part, with sonic boom generation theory (see capsule summary G-6). However, the case of non-uniform motion is discussed briefly, and these results are summarized here.

Walkden uses the expression derived by Rao (see capsule summary P-12) for the asymptotic bow shock overpressure for a body moving non-uniformly along a curved path, and makes use of Rao's finding that the F-function for a body in non-uniform curved flight is the same as for the body in uniform flight. Rao's theory was for an axisymmetric body, but Walkden extends its validity to include a wing-body combination simply by using the appropriate F-function.

P-19

PROPAGATION OF DISCONTINUITIES IN SOUND WAVES

K. E. Gubkin

Journal of Applied Math and Mechanics, Vol. 22, No.4, 1958, pp. 787-793.

The equations of motion of a compressible gas are solved in this paper to obtain the propagation of waves of small amplitude. It is assumed that the characteristic dimension of the problem is large compared to the distance behind the wavefront within which the physical variables are disturbed significantly.

The theory of geometric acoustics is used to describe the propagation of discontinuities of small amplitude. Expressions are derived for the pressure jump across the shock, $\Delta = P - P_o$, at a given point along the ray; the position of the wavefront at a given time, and the equation of the ray.

The equations show that the pressure profile behind the wave is approximately linear, and independent of the profile of the wave at the initial instant. Also, in a uniform medium at rest, the surface of the wavefront tends to become spherical as $R \to \infty$ where R is the wavefront radius, and the amplitude of the wave falls off according to the law $\Delta = B/R\sqrt{\ln R}$, where B = constant for the given ray.

This is a good brief treatment of the propagation of weak shocks in a uniform atmosphere. However, Whitham treated the propagation of weak shocks in much more depth in a previous paper (see capsule summary P-14).

P-20

GROUND MEASUREMENTS OF THE SHOCK-WAVE NOISE FROM AIRPLANES IN LEVEL FLIGHT AT MACH NUMBERS TO 1.4 AND AT ALTITUDES TO 45,000 FEET

Domenic J. Maglieri, Harvey H. Hubbard, and Donald L. Lansing, NASA TND-48, Sept. 1959

The results of flight test measurements of the sonic booms produced by two fighter airplanes in the Mach number range between 1.13 and 1.4 and at altitudes from 25,000 to 45,000 feet are presented in this paper. These results are concerned mainly with sonic boom propagation. However, human response to the booms is also considered. For a discussion of these results see capsule summary HRSC-1.

The horizontal distance from the flight track at which data were measured varied from about 2.0 to 14.0 miles. This allowed an investigation to be made of the accuracy of Whitham's theory in predicting sonic boom magnitudes at points not on the flight track and of Randall's method (see capsule summary P-21) in predicting the location at which lateral cut-off takes place.

An engineering form of Whitham's equation is used to predict the bow shock overpressure at points both on and off the flight track:

$$\Delta P_o = K_1 K_2 \frac{\sqrt{P_a P_o}}{y^{3/4}} (M^2 - 1)^{1/8} \left(\frac{d}{\ell}\right) \ell^{3/4}$$

where K_1 = ground reflection factor = $(\Delta P_f + \Delta P_r)/\Delta P_f$

ΔP_f = pressure rise across incident or free-air wave

ΔP_r = pressure rise across reflected wave

K_2 = airplane body shape factor (see capsule summary G-13)

P_a = ambient pressure at airplane altitude, psf

P_o = ambient pressure at ground level

y = perpendicular distance from measuring station to flight path, ft

M = airplane Mach number

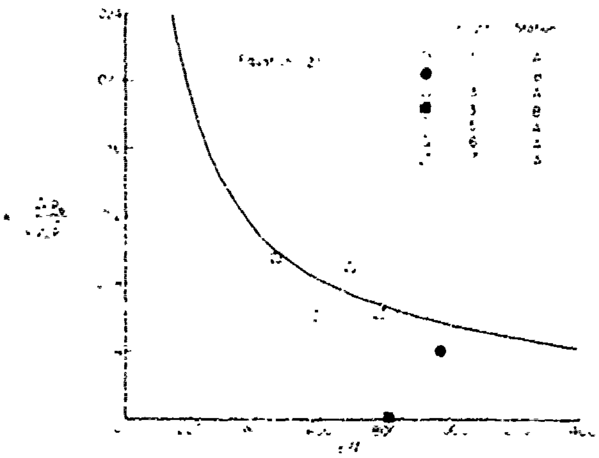
d = equivalent body diameter, ft

ℓ = airplane length, ft

This equation does not take into account the temperature and wind gradients in the atmosphere.

The figure below shows a comparison of calculated and measured values at various lateral distances from the flight track. The agreement is seen to be fairly good. The solid data points represent measurements made at least ten miles off the track. These measured values are generally lower than those calculated using the above equation. This is due primarily to the neglect of atmospheric

effects and the influence of airplane geometry on the pressure signature. The two points lying above the curve were made under conditions of high tailwinds at altitude.

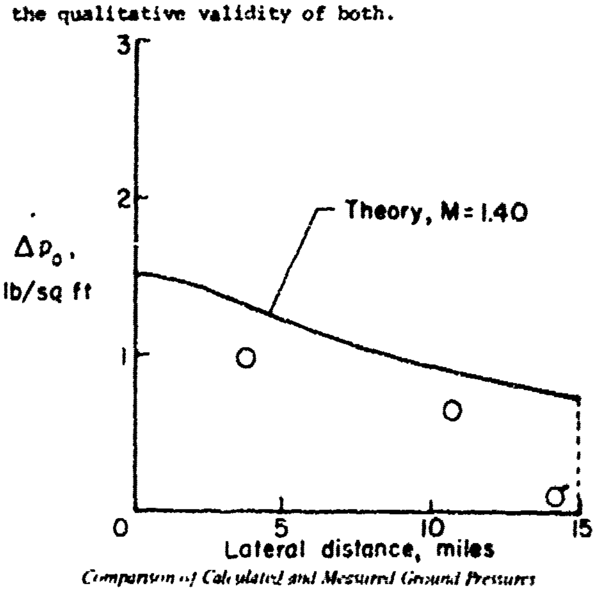


Comparison of Calculated and Measured Ground Pressures

Data from atmospheric soundings is used in conjunction with the method derived by Randall (see capsule summary P-21) to calculate ray paths for some sample cases of these tests. The effect of both temperature and winds is included in these calculations. For one of the flights for which the Mach number was 1.15 and the altitude was 50,000 feet, the calculations showed that the ray never touched the ground. The validity of this result was demonstrated by the fact that no sonic boom was measured for this particular flight.

The qualitative validity of the theory of Randall (see capsule summary P-21) in predicting the location at which lateral cut-off takes place is demonstrated in the figure below. The solid curve was calculated using the equation given earlier in this capsule summary and the lateral cut-off location is that calculated by Randall. Although the calculated values are higher than the measured values the location at which the overpressure becomes very small is in good agreement with the predicted location of lateral cut-off.

This was one of the first experimental investigations into the validity of the sonic boom propagation theories of Whitham and Randall. It demonstrated the qualitative validity of both.



Comparison of Calculated and Measured Ground Pressures

P-21

METHODS FOR ESTIMATING DISTRIBUTIONS AND INTENSITIES OF SONIC BANGS

D. G. Randall

Aeronautical Research Council Technical Report, R. & M. No. 3113, 1959

The effect of flight maneuvers and atmospheric stratification on the propagation of sonic boom is treated in this paper. All of the calculations are based upon a body of revolution having an area distribution which is typical of conventional aircraft. This area distribution is

$$S = 16\, S_m \left(\frac{n}{\ell}\right)^2 \left(1 - \frac{n}{\ell}\right)^2$$

where S_m = maximum cross-sectional area

ℓ = length of aircraft

n = distance of a section of the aircraft from the nose .

The F-function is evaluated from this area distribution and the result is used to evaluate the integral in Whitham's asymptotic formula (see capsule summary G-3). The resulting expression for the bow shock overpressure for steady level flight in a non-homogeneous atmosphere is

$$\frac{\Delta P}{\sqrt{P_a P_g}} = \frac{0.73 S_m^{1/2} M^{3/4}}{\ell^{1/4} (M^2 - 1)^{1/4} s^{3/4}}$$

where P_a = pressure at airplane altitude

P_g = pressure at ground

In this equation the effect of the variation of density with altitude has been crudely accounted for by replacing P_0, the pressure of the undisturbed air, by a geometric mean pressure, $\sqrt{P_a P_g}$.

For accelerating or maneuvering aircraft, the following equation, which results from applying the formula derived by Rao (see capsule summary P-12) to the body used in this investigation, is used:

$$\frac{\Delta P}{P_o} = \frac{0.73 S_m^{1/2} M^{3/4}}{\ell^{1/4} (M^2 - 1)^{1/4} \left[BS \left|1 - (S/\lambda)\right|\right]^{1/2}}$$

where S = distance from point of origin of sonic boom to point of reception

λ is as defined in capsule summary P-11 and B has the following forms:

$B = (-\lambda)^{1/2} \sinh^{-1} (S/-\lambda)^{1/2}$, $\lambda < 0$

$B = (\lambda)^{1/2} \sin^{-1} (S/\lambda)^{1/2}$, $\lambda > 0$, $S < \lambda$

$B = -(\lambda)^{1/2} \left[-\frac{\pi}{2} + \cosh^{-1} (S/\lambda)^{1/2}\right]$, $\lambda > 0$, $S > \lambda$

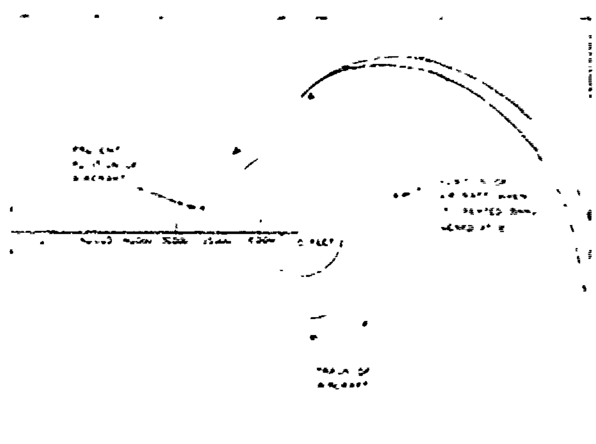
$B = S^{1/2}$, $\lambda = \infty$

An approximate expression is derived for the overpressure at a cusp, where the theory predicts infinite overpressures. This expression is:

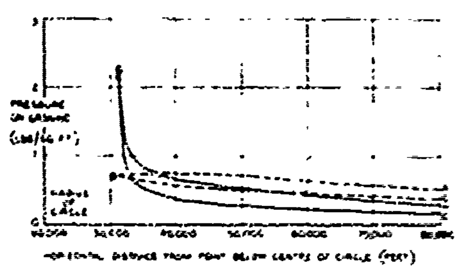
$$\frac{\Delta P}{P_o} = \frac{1.05a\ S_m^{1/2}\ M^{11/12}\ (M^2-1)^{1/4}}{\ell^{5/12}\ S^{5/4}\left|\frac{d^3S}{dt^3}\right|^{1/3}}$$

This is an engineering approximation at best and is not correct because it violates some of the basic assumptions of the theory. It predicts correct qualitative trends but it does not predict the magnitude correctly.

The first case treated is that of a horizontal circular turn at M = 1.5 at an altitude of 30,000 feet. The radius of the turn is 24,690 feet. The first figure below, which was taken from this paper, shows the position of the shock at a particular instant. It has two branches. The second figure shows a plot of overpressure versus distance. The dashed line was evaluated using Whitham's theory, which neglects the effects of acceleration. It ceases to be even qualitatively correct near the shock cusp.



Shockwave Pattern on Ground



Pressure Distribution on Ground

The cases of a sinusoidal variation of altitude and a sinusoidal variation of forward speed are also treated. The approximate results indicate that the "super-booms" produced at the cusp of the shock have intensities of two to three times the intensities predicted by Whitham's theory.

The effect of refraction on the propagation of sonic booms is then considered. The speed of sound, a, is assumed to vary with altitude according to the equation

$$a = a_g - kh$$

where k = const

and h = altitude

In such an atmosphere the disturbance is propagated along rays which are not straight lines but circles. The disturbances produced by an airplane moving supersonically have an envelope, and the rays describing the motion of the envelope are, in general, circles. Thus, even if the rays start with a downward slope, they eventually become horizontal and finally move up away from the ground. This leads to the formation of a cusp at the point at which the rays become horizontal.

The bending of the rays also leads to the phenomenon known as lateral cut-off. This refers to the limited extent of the lateral spread of the points on the ground at which the sonic boom is heard. Lateral cut-off takes place at the points on each side of the flight track at which the rays become horizontal. The following expression is derived for the lateral spread, d_m, of the sonic boom produced during steady level flight:

$$d_m = h\left(\frac{a_g + a_z}{a_g - a_z}\right)^{1/2}\left(1 - \frac{a_g^2}{V^2}\right)^{1/2}$$

where V = speed of aircraft

The final subject discussed is the effect of winds. Two cases are treated: a gradient of headwind speed and a constant sidewind. When there is no wind, no sonic boom is received anywhere on the ground if $V < a_g$. But, if the headwind speed at altitude h is Δw greater than at the ground, the speed of the aircraft must be reduced by Δw so that $V - \Delta w < a_g$. The effect of a constant sidewind is to increase the lateral spread on the side of the track toward which the wind is blowing and to decrease it by the same amount on the other side.

This is a very significant paper in the development of sonic boom propagation theory. It is significant because it presents one of the first correct treatments of the effect of a non-homogeneous atmosphere on the propagation of sonic booms.

P-22
A NEW APPROACH TO THE PROBLEMS OF SHOCK DYNAMICS. PART II. THREE-DIMENSIONAL PROBLEMS
G. B. Whitham
Journal of Fluid Mech., Vol. 5, 1959, pp. 369-386

This paper extends the theory of Part I (see capsule summary P-17) to include general three dimensional problems. The extension is only a matter of manipulating equations. The basic assumption of a functional relation between the strength of the shock wave at any point and the area of the ray tube remains the same. The theory is applied to the cases of diffraction of a plane shock wave by a cone, diffraction by a slender axisymmetric body of general shape, and the stability of a plane shock. The reader is referred to capsule summary P-17 for further details of this theory.

P-23
WEATHER ASPECTS OF THE SONIC BOOM
David Fisher
Bureau of Naval Weapons, Report No. RRSY-60-24, May 1960

A short discussion which relies upon the use of Snell's law to determine the effects of atmospheric

wind and temperature gradients upon the ray paths and sonic boom ground patterns is presented in this paper. It is shown that the effect of a standard temperature gradient, considered alone, is to alter the ground pattern from that expected for an isothermal atmosphere, the effect depending upon the flight conditions of the aircraft. At the lowest speed considered, M = 1.05, the patterns are compressed in the forward direction and extended in the lateral direction. For a 45° dive angle at M = 1.05, the effect of temperature is to distend the pattern sufficiently so that, for an altitude of 40,000 feet, the pattern is open in the forward direction. At higher speeds, the primary effect is to limit the coverage of the sonic boom on the ground; that is, for most flight conditions the temperature gradient produces a closed figure, whereas for the isothermal atmosphere the patterns are essentially parabolic. For the case where the aircraft makes a vertical dive, the circular pattern remains unchanged. However, the area covered by the boom is enlarged as a result of a temperature gradient.

The effect of wind is found to depend upon the ratio of the wind speed to the speed of sound. When the ratio is much less than unity, the effect of the wind is small. However, under certain conditions the effect of a wind gradient can be significant, when considered in conjunction with a temperature gradient.

This, along with Randall's paper (see capsule summary P-21), was among the earliest investigations into the effects of temperature and wind gradients on sonic boom propagation. This paper, however, does not treat the subject in as much depth as Randall's paper.

P-24

SOME EFFECTS OF FLIGHT MANEUVERS ON THE DISTRIBUTION OF SONIC BOOMS

Donald L. Lansing

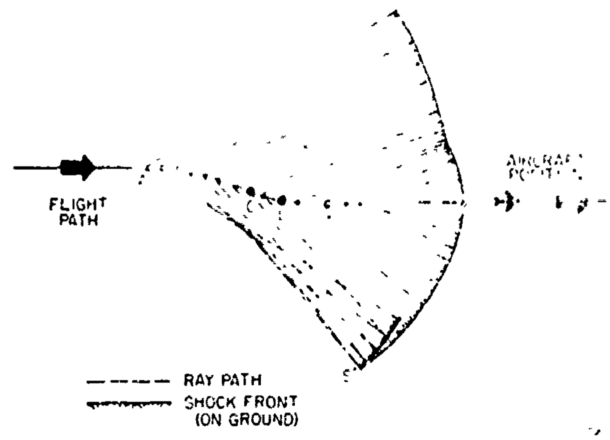
Paper presented to the Symposium on Atmospheric Acoustic Propagation, El Paso, Texas, June 13-16, 1961

This paper presents an analytical technique for predicting the ground areas most likely to experience intensified sonic booms as a result of aircraft flight maneuvers. This work is based upon the acoustic theory of sound propagation in the atmosphere.

The derivation proceeds from two basic equations. The first equation describes the shape of a single wave front expanding about an arbitrary point (x_o, y_o, z_o) of the flight path. The second equation, considered simultaneously with the first, constitutes the condition that these wave fronts form an envelope. Within the approximations of acoustic theory, this envelope represents the shock wave of the aircraft. These two equations are solved to obtain the ground shock wave pattern in terms of the aircraft position and velocity along the flight path.

Using these equations, the ground patterns for various flight maneuvers are then obtained. These cases include a horizontal sideslip maneuver, a horizontal elliptical turn, and a vertical dive.

The figure below shows a plan view of the shock front on the ground produced by a horizontal sideslip maneuver at constant altitude. Two different effects which flight maneuvers may have upon the distribution of sonic booms are clearly illustrated by this figure. The first of these is the focal point produced at point S on the shock wave. The energy originating over the portion of the flight path between points D and E is concentrated in the area in the vicinity of point S resulting in an increased shock strength. The second effect is the cusp in the shock at S', which is formed as the shock is folded back upon itself. The energy originating between points B and C of the flight path is concentrated in two shocks near the tip of the cusp.



Ground Shockwave

The horizontal elliptical turn and the vertical dive also produce cusps at certain positions on the shock ground pattern.

A qualitative indication of the relative energy concentration and shock pressures along the ground pattern are given by the convergence of the rays in the neighborhood of focal points and the overlapping of the rays which leads to cusps. It is not sufficient, however, for predicting the magnitude of the pressures in these regions. To do this, it would be necessary to take nonlinear effects into account, and this is not done in this paper.

Previous investigations dealing with the effects of flight maneuvers and acceleration on the sonic boom were conducted by Rao (see capsule summaries P-11 and P-12), Walkden (see capsule summary P-18), and Randall (see capsule summary P-21). However, these investigations were concerned mainly with the effects on the magnitude of the sonic boom rather than with the shock pattern.

The significance of this paper lies in its clear explanation and illustration of the manner in which flight maneuvers produce cusps and focal points in the ground shock pattern.

P-25

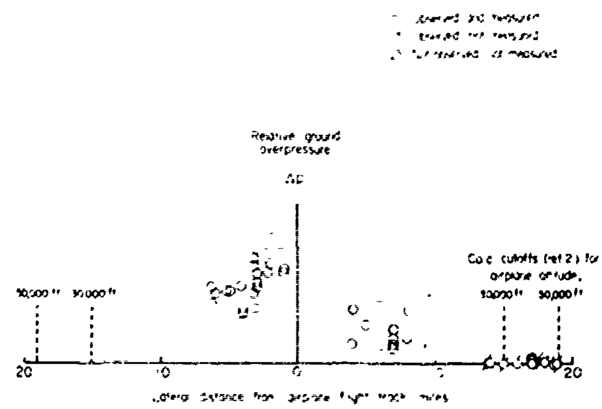
GROUND MEASUREMENTS OF THE SHOCK-WAVE NOISE FROM SUPERSONIC BOMBER AIRPLANES IN THE ALTITUDE RANGE FROM 30,000 TO [illegible]0,000 FEET

Domenic J. Maglieri and Harvey H. Hubbard

NASA TND-880, July 1961

This paper is basically concerned with lift effects on the sonic boom intensity of a B-58 bomber. For a discussion of these results see capsule summary G-16. However, the lateral spread of the sonic boom ground pattern was also investigated and these results are discussed here.

The tests were conducted at Mach numbers from 1.24 to 1.52, for altitudes from about 30,000 to 50,000 feet, and for a gross weight range from about 83,000 to 120,000 pounds. The bulk of the pressure measurements were made along the flight track of the aircraft, although some data were recorded at lateral distances up to approximately 19 miles from the flight track. In the figure below, the bow shock overpressure is plotted as a function of lateral distance from the flight track. Absolute calibration of microbarograph equipment was not available, so only the relative amplitudes of the peak pressures are given. Also shown are the calculated cutoff distances due to refraction for the altitude range of the tests based on the method of Randall (see capsule summary P-21), for which a standard atmosphere is assumed. The figure shows that the relative amplitudes of the pressures generally decrease as the lateral distance increases. The experimentally determined cutoff distances are in roughly the same range as those calculated using Randall's method.



Relative Ground Overpressure Versus Lateral Distance

In an earlier paper (see capsule summary P-20) Maglieri, Hubbard, and Lansing presented the results of flight tests which also qualitatively substantiated Randall's predictions of cutoff distances.

P-26

SONIC BOOM WAVES--CALCULATION OF ATMOSPHERIC REFRACTION
Jack.W. Reed and Kenneth G. Adams
Aerospace Engineering, March 1962, pp. 66-67 and 101-105

Equations are presented in this paper which describe the refraction of a conical acoustic wave as it propagates through an atmosphere in which the wind and temperature are horizontally stratified. The derivation is limited to the steady level flight of a body of revolution, and it is assumed that an acoustic wave is generated by supersonic flight.

An expression for the component of the horizontal wind in the azimuthal direction of a given ray is derived. (Here the azimuthal direction refers to that in the horizontal plane.) This wind component is then added to the local sound velocity to get the ray velocity. This ray velocity is then used in Snell's law (see capsule summary P-7) to calculate the refraction of the ray. As pointed out in capsule summary P-6, this approach is valid only for ground level explosions, and not for predicting the propagation of sonic booms from airplanes at high altitudes. As a result of this error, the results of the rest of the paper are invalid.

P-27

PROPAGATION OF SONIC BOOM THROUGH A NONUNIFORM ATMOSPHERE
Edward J. Kane
Boeing Airplane Company, Document No. D6-8979, May 1962

The appendices of this report present the results of a theoretical study on the propagation of sonic booms through a nonuniform atmosphere. The work was performed under a Boeing research contract by Manfred P. Friedman at MIT.

MIT Technical Report 29 contains:

1. The drivation and solution of the equations governing the strength of a shock wave as it propagates along a given ray path through a nonuniform atmosphere with wind gradients. Expressions are derived which show the dependence of shock strength on atmospheric conditions and distance travelled. These results are then combined with Whitham's to relate the shock to aircraft speed and shape.

2. The derivation and solution of the equations which govern the ray path and location of an acoustic wave (shock wave of zero strength) as it propagates through a nonuniform atmosphere with wind gradients.

3. An extension of the acoustic ray tracing results to include true shock propagation speeds instead of acoustic speeds.

4. An attempt to formulate and obtain the solution of the equations which would describe the behavior of a shock wave of finite strength in the regions where acoustic wave analysis predicts complete refractions and infinite shock strengths (superbooms).

5. A discussion of the stability of two and three-dimensional concave propagating shock fronts of small curvature.

6. An outline for the computation and combination of the above solutions.

The overall purpose of the study is to present techniques for determining the location and strength of the shock produced by an airplane flying at supersonic speeds. In general, three levels of approximation have been envisioned by the author. They are:

1. Use of acoustical ray tracing for location of the shock and an improvement to Whitham's theory (see capsule summary G-3) for determination of its strength. These two phases can be solved independently of one another by making some simplifying assumptions.

2. Use of the improved shock-strength theory with the ray path being determined by the acoustic theory equations using, however, the propagation speed giver by weak shock relations, i.e., a simultaneous solution of the shock strength and ray path equations.

3. Use of the improved shock-strength theory with the ray path being determined by the actual shock wave strength.

The latter level, though more complicated, should be valid for nearly all flight situations.

Appendix I presents the basic formulation of the problem. However, following the preparation of the report (Appendix I), some improvements and changes were made. Specifically, a coordinate system moving with the wind at the airplane altitude was used in deriving the shock strength and ray tracing equations, and an improved derivation for the ray tube area was presented. Also, a slight improvement in the equation for the prediction of the shock strength was made. These modifications are presented in additional appendices.

The attempt to describe the behavior of a shock wave of finite strength in regions where acoustic wave analysis predicts complete refractions and infinite shock strengths uses an approximation better than the acoustic one. In this approximation the propagation speed of the shock is proportional to its strength. The results of using this improved method show that complete acoustic refraction (bending upward of an initially downward propagating ray) cannot occur. This is, obviously, an incorrect result, since complete acoustic refraction does, in fact, occur. The error lies in the use of the weak shock propagation speed in the neighborhood of the caustic. In this region the shock becomes too strong for the weak-shock approximation to be valid.

In a later paper (see capsule summary P-98) Hayes also develops a method of accounting for the propagation of sonic booms through a nonuniform atmosphere. However, while the present paper merely scales the magnitude of the asymptotic bow shock overpressure to take account of atmospheric effects, Hayes' method also accounts for the influence of the atmosphere on the shape of the pressure signature as it propagates away from the aircraft.

The same material covered in MIT Technical Report 29 is also covered in a later paper by Friedman, Kane, and Sigalla, with minor modifications (see capsule summary P-33). In a later MIT report Friedman developed a computer program for implementing the theory derived here (see capsule summary P-35). Kane (see capsule summary P-42) used the theory developed in the present paper to investigate atmospheric effects on the sonic boom.

In a later paper by Eisenberg (see capsule summary P-68) it is shown that Friedman's derivation of the ray tube area in an inhomogeneous atmosphere is incorrect. The effect of this error upon Kane's results (capsule summary P-42) is very small (<10%), as shown by Hayes and Runyan (see capsule summary P-153).

In spite of its shortcomings, this was a significant paper in the development of sonic boom propagation theory because it was the first formulation of the solution for a far field N-wave through a nonuniform moving atmosphere.

P-28

ATMOSPHERIC FOCUSING OF SONIC BOOMS

Jack W. Reed

Journal of Applied Meteorology, Vol. 1, June 1962, pp. 265-267

This is a short note which presents an approximate method for determining conditions under which sonic boom focusing may occur under conditions of steady level flight. The method is based upon the determination of those conditions under which a ray emitted horizontally will be refracted to hit the ground. When this occurs it will be part of a strongly converged and compressed section of wave.

An expression is derived for the initial ray velocity for rays emitted in the horizontal plane of the airplane. It is expressed in terms of the heading angle of the airplane, the wind direction, airplane Mach number, sound speed at airplane altitude, and wind speed at airplane altitude. It is then stated that this initially horizontal ray will reach the ground, provided there are no intermediate high-velocity layers, whenever the initial ray velocity exceeds ground-level similarly directed ray velocity. An evaluation of the equation for minimum flight level wind speed for horizontally emitted rays to reach ground and give boom focusing is then made. Using these results a "safety-gram" is constructed for different flight altitudes, Mach numbers, and wind-minus-heading angle differences. When flight conditions indicate a case which falls above the appropriate curve, a ground level focus may occur. When a case falls below the curve no focus will occur.

In an earlier paper (see capsule summary P-26) Reed and Adams derived an erroneous method of calculating atmospheric refraction of sound waves. The same incorrect approximations were made in the present derivation and thus the validity of the results obtained here is questionable. Furthermore, the focusing criterion used here is actually an extreme lateral spread criterion.

P-29

ON THE ENERGY OF ACOUSTIC WAVES PROPAGATING IN MOVING MEDIA

O. S. Ryshov and G. M. Shefter

Appl. Math. Mech. (PMM), Vol. 26, 1962, pp. 1293-1309

An expression for the pressure jump at a shock front in the approximation of geometrical acoustics is derived. The dissipation of the amplitude of the wave as it propagates through a moving medium is also accounted for by the dissipation of energy in the shock.

The derivation begins with the conservation equations of mass, momentum, and entropy, together with the first law of thermodynamics. These equations are used to express the law of conservation of energy in terms of the deviations of the pressure, entropy, and velocity from their initial values due to the passage of an acoustic wave. The equation is then

simplified to the case of the motion of a thin acoustic wave through a moving medium. A thin acoustic wave is defined to be one for which the width of the zone of disturbance of the flow is small compared with the principal radii of curvature of the shock-front and with the distance at which the parameters of the initial medium are significantly changed. The resulting equation is the basic equation of geometric acoustics. It expresses the law of conservation of energy for propagation of a thin wave of small amplitude in a moving medium.

An elementary ray tube is then considered, and the rate of change of the area of the acoustic wave front as it moves along the ray tube is found in terms of the ray tube area. This is then used to find the rate of change of energy along the ray tube, which, in turn, enables the law of variation of the amplitude of the acoustic wave to be calculated. The rate of change of wavelength of the acoustic front, defined as the distance over which the disturbance caused by the wavefront takes place, is also derived in terms of the velocity of the wavefront along the ray and the initial wavelength.

The motion of a shock wave of small amplitude in the approximation beyond geometric acoustics is then considered. In this approximation the speed of a shock-front is different from the speed of propagation of an acoustic wave, and its amplitude is damped according to a different law. It is shown that the nonlinear laws of damping of shock waves in arbitrarily moving media are explained by the dissipation of energy in the shock. This is done by showing that the change per unit time of the total energy of an elementary acoustic impulse contained within a ray tube is proportional to the energy that is dissipated in the form of heat per unit time at the element of shock-front contained within the ray tube. Expressions for the laws of variation of the pressure jump across the shock and the wavelength of the shock are then derived.

All of the previous results apply to unsteady shock waves propagating in a nonhomogeneous medium. The analogous equations for steady flows are then derived.

Several of the results derived here are analogous to those derived previously by Whitham (see capsule summary P-14), Keller (see capsule summary P-8), Blokhintzev (see capsule summary P-3), and Du Mond, Cohen, Panofsky and Deeds (see capsule summary P-2). Du Mond, et al. also [illegible] the damping of a shock wave by calculating [illegible] at which it dissipated energy into heat. [illegible], they treated only the cylindrical shocks surrounding a body of revolution. The law of conservation of energy derived by Ryshov and Shefter in the present paper for the propagation of a thin wave of small amplitude in a moving medium is analogous to the invariant relation derived by Blokhintzev (see capsule summary P-3). However, Blokhintzev limits his discussion to sound waves, whereas in the present paper the relation is used to calculate the damping of the shock wave amplitude. The expression derived in the present paper for the law of variation of the amplitude of an acoustic wave is the same as that obtained by Keller from different considerations. Whitham derived an expression for the amplitude of a weak shock propagating along a ray tube at large distances from the source of disturbances. However, the analogous expression derived in this paper is valid at all distances from the body.

This is an excellent paper for determining the perturbations in physical quantities caused by the propagation of a weak shock in a moving medium.

P-30

SONIC BOOMS FROM AIRCRAFT IN MANEUVERS

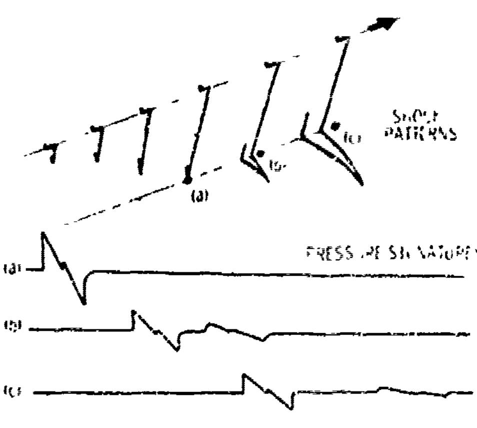
Domenic J. Maglieri and Donald L. Lansing

Sound, Vol. 2, No. 2, March-April 1963, pp 39-42

This report presents the results of flight tests conducted to check the accuracy of sonic boom propagation theory in predicting the effects of flight maneuvers. The flight maneuvers conducted in this test included linear acceleration and lateral accelerations in which the aircraft was flown in constant-speed circular turns. In each case an array of measuring instruments was located at strategic points on the ground.

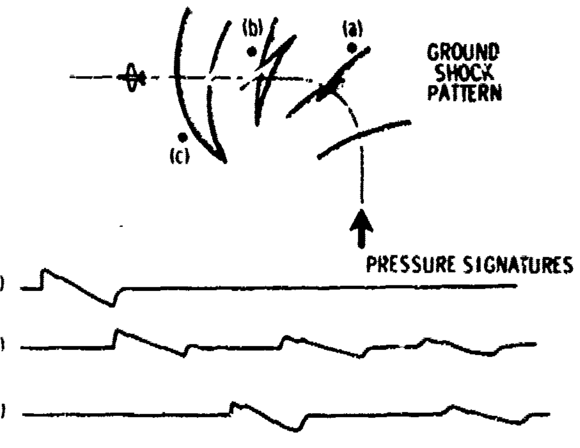
Ray path calculations were used to compute the ground shock pattern of the maneuvering aircraft. The details of these calculations are not given. The resulting ground pattern is then compared with the type of pressure signature measured at each station.

The results for the case of linear acceleration are shown in the figure below. It can be seen that there is good [illegible] qualitative agreement between the type of signature measured at each station and that which would result from the calculated ground pressure pattern. For simplicity only the bow shock is shown in the calculated shock pattern. The overpressure at point (a) is significantly greater than that at either (b) or (c). This is in agreement with the predicted location of a cusp at point (a). This figure was taken from this paper.



Longitudinal Acceleration from M = 0.95 to M = 1.2

The results for the case of constant-speed circular turns are shown in the figure below. Again, the agreement between the type of pressure signature measured at each station and that which would result from the predicted ground pressure pattern is good.



90° Circular Turn

Four significant results were obtained from the comparison of experiment and theory:

1. There was perfect agreement with regard to the number of booms observed.

2. The pressure buildup factor at a cusp was measured to be from 2 to 4, while no rigorous analytical method was available for predicting this buildup. However, an empirical estimation method predicted a factor of three.

3. The relative positions of the multiple shock waves observed during the measurements were noted to be within 1000 feet of the predicted relative positions for the on-the-track locations.

4. The location of the initial superboom impact was found to be predictable within about 2 miles when good temperature-profile and airplane-position information was available.

This is a significant paper in the development of sonic boom propagation theory because this experimental investigation was the first to investigate the effects of flight maneuvers on the shock wave pattern and intensity. The results qualitatively verify the validity of sonic boom propagation theory in predicting these effects.

P-31
THE EFFECT OF INCIDENCE ON SONIC BANG INTENSITIES
D. G. Randall
Royal Aircraft Establishment Tech. Note No. Structures 332
April, 1963

In 1961 Randall and Warren wrote an article entitled "The Theory of Sonic Bangs" (see capsule summary P-45), which summarized the advances made in the theory up to 1960 and extended Rao's theory (see capsule summaries P-11 and P-12) to include the effects of lift and a nonhomogeneous atmosphere. Section 5 of that article, which dealt with the extension to an aircraft with lift, is largely incorrect. In the present paper Randall corrects the results of that article and discusses the application of the theory to the two simple cases of an elliptical cone at incidence and a wing-body combination consisting of two flat plates mounted symmetrically on a circular cone.

In 1964 Warren also published a correction for the same error. His correction is, basically, the same as Randall's, and the reader is referred to capsule summary P-45 for the details.

P-32
THE EFFECT OF METEOROLOGICAL VARIATIONS ON THE STATISTICAL SPREAD IN THE INTENSITY OF BANGS AT LARGE DISTANCES FROM THE SOURCE
C.H.E. Warren
Royal Aircraft Establishment Technical Note No. Structures 334, May 1963

This paper presents a brief discussion of atmospheric effects on the spread in sonic boom intensities. The discussion is based upon data obtained in earlier flight tests conducted in the United States and data from high altitude explosions conducted in the United Kingdom. It is concluded that the limited evidence suggests that meteorological variations within the atmosphere can cause appreciable statistical spread in the sonic boom intensities on the ground. For a supersonic aircraft flying at 50,000 feet, a statistical spread in the values of boom intensity corresponding to a standard deviation of about 1.3 should be expected. This means that 1% of the time the sonic boom intensity will be greater than the mean value by a factor of 1.85.

In a later paper (see capsule summary P-61) Dressler and Fredholm present a much more extensive investigation into the effect of atmospheric variations on the statistical spread in sonic boom intensities.

P-33
EFFECTS OF ATMOSPHERE AND AIRCRAFT MOTION ON THE LOCATION AND INTENSITY OF A SONIC BOOM
Manfred P. Friedman, Edward J. Kane, and Armand Sigalla
AIAA Journal, Vol. 1, No. 6, June 1963, pp. 1327-1335

The problem of a shock propagating through a nonuniform atmosphere is considered in this paper. Methods are derived for calculating the shock strength and location as a function of its initial configuration, the distance it has traveled, and the atmosphere through which it has propagated.

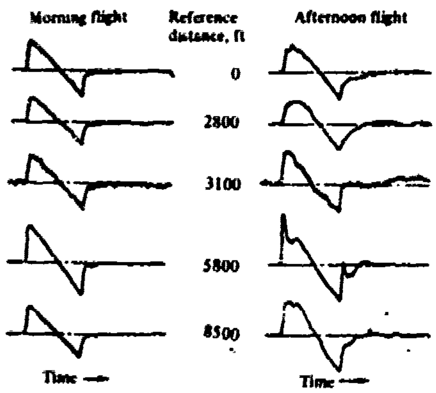
This paper covers essentially the same material covered in an earlier document by Kane and Friedman (see capsule summary P-27). The reader is referred to that capsule summary for details of this theory.

P-34
ATMOSPHERIC EFFECTS ON SONIC-BOOM PRESSURE SIGNATURES
Domenic J. Maglieri and Tony L. Parrott
Sound, Vol. 2, No. 4, July-August 1963, pp. 11-14

Flight test results which show the effect of atmospheric conditions on the sonic boom pressure signature are presented in this paper. These results deal with steady level flight only.

Sonic boom ground-pressure signatures were obtained for a wide variety of temperatures and wind profiles in the lower atmosphere. The results indicate a strong correlation between the peak overpressure, the type of signature measured, and the existing temperature profile in the lower atmosphere. Consistent N-wave types of signatures and peak overpressure values were measured for a

morning flight when the lower atmosphere was quiescent, whereas relatively large variations occurred for an afternoon flight when the lower atmosphere was judged to be unstable, as shown in the figure below, which was taken from this paper. The gross shapes and location of the wave-front ground-intersection patterns compare fairly well with calculations made assuming a homogeneous atmosphere, although some local variations or ripples were observed.



Ground Track Signatures for M = 1.9 at Altitude of 51,000 Feet

In a later paper (see capsule summary P-36) the results of these same flight tests are discussed in much more depth.

This was one of the first experimental investigations into the effect of the atmosphere on sonic boom pressure signatures.

P-35
A STUDY OF ATMOSPHERIC EFFECTS ON SONIC BOOMS
Manfred P. Friedman
MIT Technical Report 89, December 1963.

A computer program is presented in this paper which implements the non-uniform atmosphere propagation theory derived in an earlier paper (see capsule summary P-33). A reproduction of the earlier paper is contained in the appendix.

The "Sonic Boom Computer Program" uses the following input data:

1) Aircraft parameters such as altitude, Mach number, aircraft length and weight, acceleration rate, and volume and lift factors.

2) Atmospheric temperature, pressure, and winds between the ground and the aircraft, and the shock-ground reflection factor.

3) The initial ray directions, specified by giving those angles for which computations are desired, measured around the flight direction. This input is necessary because the analysis is based on ray tube concepts, i.e., a small segment of shock is considered to be propagating down a ray tube and its strength and location are determined along the ray path until it strikes the ground.

The computer output gives:

1) A listing of pertinent input data.

2) The strength and location of the shock corresponding to a selected input angle at intermediate computed points between the aircraft and the ground.

3) The location and strength of the shock at the shock-ground intersection.

This computer program has become outdated since the introduction of Hayes' computer program (see capsule summary P-98).

P-36
LATERAL-SPREAD SONIC-BOOM GROUND-PRESSURE MEASUREMENTS FROM AIRPLANES AT ALTITUDES TO 75,000 FEET AND AT MACH NUMBERS TO 2.0
Domenic J. Maglieri, Tony L. Parrott, David A. Hilton, and William L. Copeland
NASA TN D-2021, 1963

This paper presents measurements of overpressures and shock arrival times for both fighter and bomber airplanes in the Mach number range 1.1 to 2.0 and for altitudes from 10,000 to 75,000 feet for measuring stations both on the flight track and at lateral distances out to about 20 miles.

The following conclusions were reached as a result of these measurements:

1) Although some scatter was noted in the data at large lateral distances, measured overpressures for both the fighter and bomber were maximum under the flight path, and decreased generally with increasing lateral distance. A comparison with volume theory calculations indicated that the fighter airplane data were in good agreement with the theory in the vicinity of the flight track and, as predicted by theory, decreased in magnitude with increasing lateral distance. For the bomber, the measured data on the track were markedly higher than the values calculated by volume theory but drop off in magnitude with increasing lateral distance at a relatively faster rate than the calculated values. It is concluded that these results point up the fact that the lift effects are more significant for the bomber than for the fighter and that the lift effects are most significant at locations along and near the ground track.

The data were not detailed enough to properly define the lateral cut off experimentally. The results are, however, in general agreement with those predicted by theory on the basis of atmospheric refraction (see capsule summary P-21). The limited data available do not indicate a sudden decrease in the pressures near the cut-off point as suggested by theory.

2) The atmospheric effects were found to cause an increase in the angles of incidence of the shock waves at the ground and relatively small ripples in the wave fronts. No large distortions of the wave front were detected.

3) Ground reflection factors on the airplane ground track varied between 1.8 and 2.0, whereas at extreme lateral distances there was evidence that the reflection factor decreased to a value approaching 1.0.

4. Although considerable scatter existed in the data, the rise times generally increased as the airplane altitude increased.

In an earlier paper (see capsule summary P-34) Maglieri and Parrott discussed the atmospheric effects on the pressure signatures measured during these same flight tests. The main conclusion was that consistent N-wave types of signatures and peak overpressure values were measured when the lower atmosphere was quiescent, whereas relatively large variations in signature shape occurred when the lower atmosphere was judged to be unstable.

This is a significant paper because it presents an in-depth discussion of the results of one of the first-flight test investigations to be conducted with the purpose of determining atmospheric effects on the sonic boom pressure signature.

P-37
THE EFFECTS OF FLIGHT PATH AND ATMOSPHERIC VARIATIONS ON THE BOOM PROPAGATED FROM A SUPERSONIC AIRCRAFT
Raymond L. Barger
NASA TR R-191, February 1964

The effects of flight maneuvers and atmospheric variations on the propagation of sonic booms are analyzed in this paper. The theory of geometric acoustics (see capsule summaries P-1, P-8, or P-10) is used to derive equations for the shock wave envelope and cusp line associated with the boom propagated from a supersonic aircraft flying in a uniform atmosphere and also in an atmosphere with a linear sound speed gradient. The theory of geometric acoustics is also used to derive a general expression for the ray tube area in an atmosphere in which the temperature and winds are stratified and only head winds or tail winds (not crosswinds) exist. This expression is then used to calculate the lateral distribution of boom intensity. The relative importance of wind and temperature effects is then treated, and the mechanisms of focusing by winds and by ground structures are discussed qualitatively.

The following conclusions were reached as a result of this analytical investigation:

1. At the altitudes and Mach numbers of interest in connection with flights of a supersonic transport at or near cruise conditions, superboom effects due to acceleration, turns, or atmospheric refraction should be negligible. However, in the low supersonic range, all of these effects, in addition to that of changing altitude, may influence the boom intensity.

2. The wind becomes relatively more important in refracting the ground-track rays as the Mach number increases. Focusing of ground-track rays (which are initially parallel) can be caused by the temperature gradient, or by a combination of wind and temperature gradients.

3. Cusp points off the ground track cannot be caused by a linear sound-speed gradient, but when the combination of flight altitude and Mach number is such that the ground pattern is relativley narrow, then it is possible that the intensity off the flight track will be greater than on it. Focusing of slightly inclined rays at a considerable distance from the flight track can occur in the presence of a strong wind gradient.

4. Focusing may also occur as a result of reflection from certain forms of terrain or ground structures.

In related previous papers Rao (see capsule summaries P-11 and P-12) made an analysis based on geometrical acoustics for a uniform atmosphere of the conditions for focusing resulting from aircraft acceleration or turning maneuvers, together with an estimate of the intensity of the boom at the focal points. However, the present paper discusses not only the conditions for cusp formation but also the actual spatial distribution of the cusp line and the derivation of the parametric equations for this line. Randall (see capsule summary P-21) studied the effects of a linear sound speed variation with altitude and Friedman (see capsule summary P-27) included the effects of both sound-speed variations and wind gradients. Lansing (see capsule summary P-24) dealt with the manner in which flight maneuvers produce cusps and focal points in the ground shock pattern, and Maglieri and Lansing (see capsule summary P-30) presented flight test results which tested the effects of aircraft maneuvers on the sonic boom intensity. This paper brings together and expands upon many of the results of these previous papers.

P-38
SONIC BOOMS FROM AIRCRAFT IN MANEUVERS
Domenic J. Maglieri and Donald L. Lansing
NASA TN D-2370, July 1964

The results of flight tests conducted to check the accuracy of sonic boom propagation theory in predicting the effects of flight maneuvers are presented in this paper. The maneuvers conducted in this test included linear acceleration and lateral accelerations in which the aircraft was flown in constant-speed circular turns. In each case an array of measuring instruments was located at strategic points on the ground.

This report is exactly the same as an article which appeared earlier in "Sound". The reader is referred to capsule summary P-30, which describes that paper, for further details of this investigation.

P-39
ATMOSPHERIC SCATTERING OF SONIC BOOM INTENSITIES
Robert F. Dressler and Nils Fredholm
ICAS Paper No. 64-583, Aug. 1964

The prediction of the magnitudes and frequencies of the scatter about average values for sonic boom intensities at ground level caused by variable atmospheric temperature and wind conditions is dealt with in this paper. The first two-thirds of the paper is the same as an earlier report by Dressler (see capsule summary P-44). This portion of the paper shows that the exact formulation of geometric acoustics which distinguishes betwee wave normals and rays should be used in sonic boom calculations, rather than the Rayleigh approximation, which makes no such distinction. It is also shown that, for an at-

mospheric model in which the wind and temperature increase linearly with altitude, the overpressure magnification factor due to winds varies from a peak value of 0.91 for tailwinds to a peak value of 2.21 for headwinds. The reader is referred to capsule summary P-44 for further details of this work.

The final portion of the paper deals with the scatter produced by a "realistic" "global" atmospheric model for temperature and winds. After describing this atmosphere in detail, the specific case of Mach number equal to 2.2 and altitude equal to 50,000 feet is chosen and results are obtained for the scatter in overpressure and scatter in the points on the sonic boom ground carpet where the peak overpressure occurs. The results for the ground distance from flight path to the line of maximum intensity show a normal distribution in the probability density curve between 0 and 10,000 feet, but the remaining 20% of the cases lie stretched over a wide interval from 45,000 feet up to about 100,000 feet. Thus 20% of the boom peaks strike outside a band about 17 miles wide beneath the airplane.

This paper, along with the previous paper by Dressler (see capsule summary P-44), was the first to treat in a statistical manner the scattering of sonic boom intensities due to winds. The overpressure magnification investigated here was not the "spiking" or "rounding" effect caused by turbulence, but rather the change in shock strength due to a change in ray tube area. However, the ray tube relationship used to account for overpressure increases is somewhat inaccurate. The energy conservation approach used in this paper leads to the conclusion that overpressure is proportional to the ray tube area. This method somewhat overestimates overpressures because it does not take into account the aging of the pressure signature or lateral spreading of the energy.

P-40

A NOTE ON THE PROPAGATION OF SOUND RAYS IN A MOVING MEDIUM

George H. Gilbert

Journal of Applied Meteorology, Vol. 3, August 1964, pp. 484-485

Snell's law for the propagation of sound rays in a stratified medium is often assumed to take the following form (see capsule summaries P-7, P-16, and P-26, for example):

$$V \sec\theta + u = \text{Const}$$

where V = speed of sound

θ = inclination of sound ray to horizontal

and u = component of wind velocity in direction of propagation

The horizontal distance traveled by the sound ray is then usually obtained by evaluating

$$x = \int \cot\theta \, dz$$

where z = altitude

The purpose of this note is to indicate the assumptions underlying these equations and the extent to which they are valid.

In the correct Snell's law for a stratified moving medium the correct angle to use is the inclination of the wave-front normal to the horizontal. The use of the first relationship therefore assumes that the direction of ray is a good approximation to the wave-front normal.

The relationship between the wave normal inclination angle ϕ and the ray inclination angle θ is given by

$$\cot\theta = \cot\phi + \frac{u}{V}\operatorname{cosec}\phi$$

Thus the use of the approximate relationship for the horizontal distance of travel by the ray assumes that the contribution due to the translational effect of the wind may be neglected in comparison to the contribution due to refraction.

The validity of both of the assumptions depends upon the magnitude of the winds and the initial inclination angle of the ray. However, in most cases the approximation does not lead to significant errors.

P-41

THE PROPAGATION OF SONIC BANGS IN A NONHOMOGENEOUS STILL ATMOSPHERE

C. H. E. Warren

ICAS Paper No. 64-547, August 1964

The propagation of sonic booms in an atmosphere where the temperature varies with altitude but which has no winds is studied in this paper. Snell's law is used to derive the ray equations in such an atmosphere. The effects of aircraft acceleration are included in the derivation. The ray equations are then used to investigate the conditions of grazing, where a refracted ray becomes horizontal at ground level, and focusing, which occurs when adjacent rays intersect. Equations are derived which give the locus of ground points at which grazing or focusing occur.

The extension of Whitham's results for the bow shock overpressure (see capsule summary G-3) to an atmosphere in which the temperature, pressure, and density vary with altitude is then briefly discussed. The only modifications made are the replacement of ambient pressure P_∞ by a geometric mean pressure $\sqrt{P_a P_g}$, where P_a and P_g are respectively the ambient air pressures at altitude and at ground level; and the use of the distance along the ray instead of the perpendicular distance from the flight path.

Finally, the effects of ground reflections, as exemplified by the reflection factor K_r, and the effects of aircraft shape and lift are touched upon.

In an earlier paper Warren and Randall (see capsule summary P-45) extended Rao's theory concerning the sonic boom of an accelerating airplane (see capsule summary P-11) to include the effects of lift and an atmosphere in which the temperature decreased linearly with altitude. However, the topics of grazing and focusing were not dealt with in that paper.

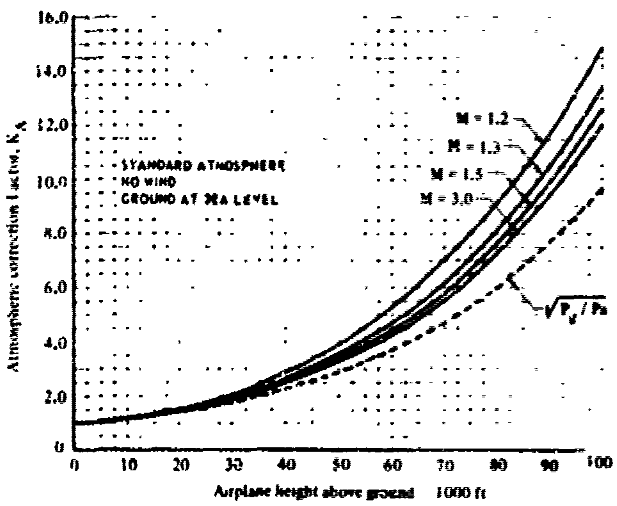
This is a good brief treatment of the effects of an atmospheric temperature gradient on sonic

boom propagation, but the neglect of the effects of winds limits the usefulness of the theory developed here.

P-42
METEOROLOGICAL ASPECTS OF THE SONIC BOOM
Edward J. Kane and Thomas Y. Palmer
FAA SRDS Report No. RD-64-160, September 1964
(Available from DDC as AD-610463)

The effects of varying meteorological conditions on the intensity and spread of the sonic boom are investigated in this report. This is accomplished by constructing several stratified atmospheric models and comparing sonic boom calculations in these atmospheres with results in the U. S. Standard Atmosphere, 1962. In conjunction with the Standard Atmosphere, an atmospheric correction factor, K_A, is derived. This factor corrects the magnitude of the bow shock overpressure given by Whitham's asymptotic formula (see capsule summary G-3) to account for the non-uniform atmosphere effects.

Thus the corrected bow shock overpressure is given by $P = K_A P_{Whitham}$. K_A is a function of the ambient atmospheric pressure, temperature, airplane Mach number, and height above the ground. The variation of this factor was calculated by the method given in capsule summary P-33, and is shown in the figure below, for the ground located at sea level.



Atmospheric Correction Factor for U.S. Standard Atmosphere, 1962

It is found in this study that the influence of wind and temperature variation from standard conditions is primarily a function of Mach number, while the influence of pressure variation is independent of Mach number. It is also determined that for flight at Mach numbers above 1.3 the largest influence of varying the meteorological conditions from those in the Standard Atmosphere is a change in the sonic boom overpressure of about 5 percent. Flight at Mach numbers below 1.3 may result in more significant variations.

The meterological conditions required to produce focusing, complete cutoff, extreme lateral spread, and deformation of the pressure signature are investigated and methods for predicting the occurrence of these conditions are established.

It is found that realistic variations in temperature and winds can produce focusing or complete cutoff for flight at Mach numbers below 1.3. Focusing will occur simultaneously with cutoff where the shock waves are normal to the ground, and the normal doubling of the overpressure due to oblique shock wave reflections will not occur in this region. Extreme lateral spread and deformation of the pressure wave due to interactions with turbulence may occur at all Mach numbers. The former will not occur, however, for flight at altitudes above those where the maximum winds exist, regardless of the Mach number.

A number of comparisons are made with flight test data obtained during the Oklahoma City flight test series. Predicted and measured pressure wave signatures are compared for each test airplane. It is generally found that the pressure rise, length, and slope of the expansion region between the shocks of the measured wave agree closely with the predicted wave. It is stressed that when comparing experiment with theory it is necessary to compare the entire pressure signatures, rather than just the magnitude of the bow shock overpressure.

The presence of turbulence near the ground results in the deformation of the incoming pressure signature, and some of these deformed signatures are analyzed. A statistical analysis of these data indicates that the important scattering parameters are the angle of the path of the shock wave and the time of day as related to the turbulent intensity near the ground.

The theoretical basis of this report is, basically, that developed in capsule summaries P-27, P-33, and P-35. Numerous simplified equations are derived throughout this report expressing various atmospheric effects on sonic boom propagation, and nearly all of these derivations proceed from the basic theory developed in the above-mentioned capsule summaries.

This report was the most extensive written up to 1964 concerning the effects of a nonuniform atmosphere on the propagation and intensity of sonic booms. The atmospheric correction factor K_A developed here gained subsequent widespread use. It must be remembered, however, that the factor K_A is only applicable to the pressure signature after it has reached its asymptotic form and is governed by Whitham's asymptotic equation (see capsule summary G-3).

A summary of the work of the present paper is presented in a later paper by Kane (see capsule summary P-74).

P-43
APPLICATION OF ACOUSTIC THEORY TO PREDICTION OF SONIC BOOM GROUND PATTERNS FROM MANEUVERING AIRCRAFT
Donald L. Lansing
NASA TND-1860, October 1964

The purpose of this paper is to discuss two methods for determining the ground shock wave patterns produced by a maneuvering aircraft, based upon the acoustic theory of the propagation of weak disturbances in an atmosphere having a linearly decreasing sound speed. This paper makes considerable use of the results of Randall (see capsule summary P-21).

The ray equations are derived first, beginning with Fermat's "Principle of Least Time," which states that the path taken by a disturbance traveling between two points in an inhomogeneous atmosphere is the one which requires the least time. The equations for the ray path and the time required for the shock to reach a given point on the ray are used to investigate the ground patterns of the shock waves produced in both level and inclined flight. This results in a graphical procedure involving ray tracing which gives some physical insight into the manner in which the ground patterns are formed.

A ballistic wave approach, in which the main point of interest is the wave fronts rather than the rays, is then described. In this approach a set of parametric equations is obtained which describes the entire shock wave. This set of equations is then used to determine the equations describing the coordinates of the ground intersection pattern and a vertical cross section of the shock wave when the flight path lies in a vertical plane. From these equations several examples are worked out to show the effects that typical flight maneuvers may have upon the ground shock patterns.

This paper is very similar to an earlier paper by Lansing (see capsule summary P-24), except that the ray theory method was not discussed in that paper. The reader is referred to capsule summary P-24 for further details of the work of the present paper.

This paper presents not only a good mathematical derivation of the effects of aircraft maneuvers on sonic boom ground patterns but also a good physical explanation of these effects.

P-44
SONIC BOOM WAVES IN STRONG WINDS
Robert F. Dressler
FFA Report 97, 1964.

This paper treats the propagation of sonic booms in an atmosphere in which the wind velocity is increasing linearly with altitude and has the same direction at all altitudes, and the temperature varies linearly with altitude. The theory of geometric acoustics (see capsule summaries P-1, P-8, and P-10, for example) is briefly reviewed and is used to show that when wind velocities are large and wavefront directions are obliquely inclined to the wind, the directions of rays and wave normals will diverge considerably and a careful distinction must be made between the two. Reed and Adams failed to make this distinction (see capsule summary P-26), and much of the remainder of the present report is devoted to comparing the incorrect results of Reed and Adams with the correct results obtained in the present paper by use of the correct form of Snell's law. (The approximation to Snell's law made by Reed and Adams used the ray direction instead of the wave normal direction, whereas no such approximation was made in the present paper). For a crosswind and a tailwind inclined at 45° to the flight path, the calculations of Reed and Adams showed a focusing effect at the lateral extremity of the shock-ground intersection on the downwind side of the ground track. The results of the present paper, however, do not predict any focusing or strong magnifications for these cases. They do predict a much larger lateral spread.

The peak value for overpressure magnification is then calculated for each of five wind directions assuming the airplane model and Mach number are held fixed. The results range from about 0.91 for the tailwind, 1.00 for the crosswind, to 2.21 for the headwind. It is then shown that, when the angle of incidence between the shock wave and the ground is taken into consideration, the peak energy intensity which is delivered to the horizontal ground area is the same for all five wind directions. In conjunction with this result it is suggested that more attention should be given to measurements of approach angles for sonic booms as well as overpressure measurements for the evaluation of sonic boom damage.

Dressler developed a computer program which uses the correct form of Snell's law in conjunction with an atmospheric model in which the temperature and winds are horizontally stratified. No details of the program are given in this paper, however.

The theoretical method used in this paper to take account of the effects of temperature and wind gradients on sonic boom propagation is similar to that developed earlier by Friedman (see capsule summary P-27). However Friedman's treatment of the subject is much more extensive, and Friedman, in addition to developing a theory based on geometric acoustics, also developed an improved theory based upon the use of more exact shock propagation speeds. Furthermore, the overpressure calculations in the present paper use an energy conservation approach which leads to the overpressure being proportional to the ray tube area. This method somewhat overestimates overpressure because it does not take into account the aging of the pressure signature or lateral spreading of the energy.

P-45
THE THEORY OF SONIC BANGS
C. H. E. Warren and D. G. Randall
Prog. Aeronautical Sci., Vol. 1, 1961, pp. 238-274
and Prog. Aeronautical Sci., Vol. 5, 1964,
pp. 295-302

This paper reviews Rao's theory (see capsule summary P-11) concerning the sonic boom of an accelerating airplane and extends it to include the effects of lift and a nonhomogeneous atmosphere.

The complete derivation, as performed by Rao for the overpressure of an accelerating airplane with negligible lift in a homogeneous atmosphere, is presented. The extension to an aircraft with lift is then made. However, in making this extension it is erroneously assumed that the strength of a transient doublet at any point on the flight path is proportional to the lift on the cross-section of the aircraft momentarily at that point. Thus in 1964 Warren published a complete correction to this section of the paper (see second reference listed above). The important result of the corrected section is the derivation of the expression for the F-function of an accelerating lifting aircraft.

This expression for the F-function can be substituted into the expression derived by Rao (see capsule summary P-11) to obtain the overpressure. An expression is also obtained for the

improved characteristics, using the same technique used by Whitham (see capsule summary G-3) to correct the linear theory characteristics. The shocks are determined from the improved characteristics and the Rankine-Hugoniot relations, also in the manner of Whitham.

It is then assumed that the speed of sound decreases linearly with altitude, and the modifications to the theory resulting from such an assumption are investigated. Equations are derived for the wavefronts and rays resulting from moving sources of disturbances in such an atmosphere. The derivation is nearly identical to that made by Randall in a previous paper (see capsule summary P-21). The final result is the modification of the expression for the velocity potential to account for the inhomogeneous atmosphere.

This paper presents a good summary of sonic boom propagation theory as of 1961. However, it is important to note that this work deals only with the modifications to the asymptotic form of the pressure signature due to the effects of airplane acceleration and nonuniform atmosphere. Thus it predicts only front shock overpressure and not signature details.

P-46

SOUND RAYS IN THE ATMOSPHERE

R. J. Thompson

Sandia Corporaton Research Report, SC-RR-64-1756, January 1965

A system of ordinary differential equations describing ray paths in the presence of vertically varying winds is derived in this report. Some comments are made regarding the Rayleigh approximation and its relationship to the equations derived here.

The ray equations are derived from the continuity and momentum equations of hydrodynamics. It is assumed that the sound speed and wind vary with altitude. The derivation is concerned mainly with the propagation of disturbances from ground level explosions.

Rayleigh's approximation to Snell's law is

$$c \sec \theta + U = k$$

where c = sound speed
U = horizontal wind speed
k = constant
and θ = inclination angle of ray to horizontal.

Thus, in this approximation the ray inclination angle is used instead of the more correct wave normal angle. In making this approximation Rayleigh was treating only rays which are almost parallel to the wind direction. The author of the present paper concludes that Rayleigh's approximation may be used only when θ is small. Two example calculations are then performed for a ground explosion which compare the ray paths given by Rayleigh's approximation to those given by a more exact expression derived from the ray equations. In general the rays look much alike except that those given by Rayleigh's approximation hit the ground at a shorter distance from the explosion.

Rayleigh's approximation was used by Cox, Plagge, and Reed (see capsule summary P-7) to calculate the propagation of disturbances from ground explosions, as did Cox (see capsule summary P-16). However, Reed and Adams tried to use this approximation to calculate the propagation of sonic booms from airplanes at high altitudes, and, as a result, their results were incorrect (see capsule summary P-26).

P-47

A DESCRIPTION OF A COMPUTER PROGRAM FOR THE STUDY OF ATMOSPHERIC EFFECTS ON SONIC BOOMS

Manfred P. Friedman

NASA CR-157, February 1965

This report is very similar to MIT Technical Report 89 (see capsule summary P-35). However, this report does not contain the complete theoretical background for the computer program, while the previous report does. Results of several example calculations are given, and, in addition, the results of the previous report are extended to include flight paths which are curved, climbing, or diving (see capsule summary P-51 for a discussion of this extension).

"Improved" expressions for the pressure jump and ray-tube area, as compared to those of the earlier report, are derived and used. However, as shown by Haglund (see capsule summary P-104) the "improved" expression for the ray tube area gives erroneous results.

For further details of this theory the reader is referred to capsule summary P-35.

P-48

COMPARISON OF MEASURED AND CALCULATED SONIC-BOOM GROUND PATTERNS DUE TO SEVERAL DIFFERENT AIRCRAFT MANEUVERS

Donald L. Lansing and Domenic J. Maglieri

NASA TND-2730, April 1965

In this paper the acoustic theory developed previously by Lansing (see capsule summary P-43) is used to calculate ground pressure patterns from aircraft in maneuvers which are then compared with measured results of flight tests. The magnitudes of the bow shock overpressures are calculated using a modified form of Rao's expression (see capsule summaries P-11 and P-12) which attempts to take into account the inhomogeneity of the atmosphere. The modifications consist of the use of $\sqrt{P_a P_o}$, where P_a is the pressure at the altitude where the shock was generated and P_o is the pressure at the ground, instead of P , which is the pressure in the indisturbed air in a homogeneous atmosphere, and the use of c and M as the speed of sound and aircraft Mach number at the altitude and time at which the observed shock was generated.

The flight tests were conducted at Edwards Air Force Base using a supersonic fighter (the paper does not specify which fighter was used). The maneuvers conducted included pushover-dive-pullout, longitudinal acceleration, pullup-climb-pushover, and circular turn maneuvers. For each maneuver, calculations of the arrival time of the shock wave and the pressure amplitude as a function of distance along the ground are compared with the measurements from an array of microphones. The comparison indicates that the theoretical method used is capable of predicting the essential fea-

tures of the ground shock patterns of aircraft in maneuvers at altitudes below 30,000 to 40,000 feet, at least when the sound speed gradient is nearly linear. In particular the theory predicts the correct number of N-waves which will occur in the vicinity of a given ground area and gives reasonable estimates of the time elapsed between the generation of the boom and its arrival on the ground. In general, the calculated elapsed times are a few seconds less than those measured. The calculated overpressures either agree well with measurements or give a slight overestimate in those ground areas which do not experience superbooms. The results suggest that the location of superbooms can be predicted to within plus or minus 2 to 3 miles, provided accurate aircraft position and weather data are available.

An earlier paper by Maglieri and Lansing (see capsule summary P-30) also used acoustic theory to compare calculated and measured ground patterns. The results qualitatively verified the validity of using acoustic theory to predict the propagation of sonic booms from aircraft in maneuvers. The present paper, however, compares theory and experiment quantitatively rather than qualitatively.

This is a good experimental verification of the essential validity of acoustic theory.

P-49

ATMOSPHERIC EFFECTS ON SONIC-BOOM SIGNATURES

Domenic J. Maglieri and Harvey H. Hubbard

5e Congres International D'Acoustique, Liege, September 7-14, 1965

Data from flight tests are used in this paper to illustrate the nature of various atmospheric effects on sonic boom pressure signatures. The measured results discussed here are all gleaned from previous experimental investigations.

The effect of a longitudinal acceleration is treated first. Cusp formation and the ground pressure patterns at various points along the flight track are discussed. The overpressures measured in the vecinity of the superboom were found to be as high as 2.5 times those of the unmagnified booms.

Lateral spread patterns are then discussed and it is shown that, as predicted by theory, the overpressures decrease with increasing lateral distance from the flight path and drop to zero near the lateral cut-off location.

The effect of atmospheric turbulence on sonic boom pressure signatures is shown to manifest itself in either a "spiking" or a "rounding" of the initial pressure peak. A large number of data points for a range of flight conditions are then used to make a statistical analysis of the variations of overpressure amplitude. This analysis shows that a wider variation in amplitude occurs for the stations more remote from the flight track. The variation in amplitude for the bomber data, which have markedly longer wavelengths than those of the fighter, is found to be only slightly less than that for the fighter. Human response phenomena are then briefly discussed.

Kane (see capsule summary P-42) treated atmospheric effects on sonic booms in much more depth than the present paper. However, it does give a good brief overview of the subject.

P-50

EFFECTS OF GROUND REFLECTION ON THE SHAPES OF SONIC BANGS

E. J. Walker and P. E. Doak

Paper No. L55, Presented at 5e Congres International D'Acoustique, Liege, September 7-14, 1965

An investigation of the effects of ground reflection on the shapes of sonic booms is presented in this paper. The main effect is shown to be the distortion of the reflected waveform due to the presence of reactance (or a frequency dependent resistance) in the normal acoustic impedance of a partially absorbing surface. Since there was practically no published information on the values of the resistive and reactive components of the impedance of representative ground surfaces, some measurements were carried out, using an impedance tube, of the normal acoustic impedance of various ground samples, with various moisture contents. his data was then used to predict the shapes of reflected N-waves using a simplified theory.

The results showed that appreciable distortion of the reflected wave due to ground reflection effects occurs only at angles near grazing incidence. **The distortion consists of a rounding of the waveform.**

This is a significant paper in that this was the first investigation of the effects of ground reflection on sonic boom signature shape.

P-51

A METHOD FOR CALCULATING THE EFFECT OF AIRCRAFT MANEUVERS ON SONIC BOOMS

Charles J. Bartlett and Manfred P. Friedman

Journal of Aircraft, Vol. 2, No. 5, September-October 1965, pp. 353-356

The theory developed by Friedman, Kane, and Sigalla in an earlier paper (see capsule summary P-33), which provides a method of calculating the propagation of sonic booms from aircraft in steady or accelerating level flight in a nonhomogeneous atmosphere and takes account of both wind and temperature gradients, is extended in this paper to include the effects of diving and climbing aircraft on curved flightpaths.

Equations expressing the ray angle geometry in terms of the airplane climb angle, Mach angle, and initial ray direction are derived first. The effect of flight path curvature on the ray inclination angle is then determined. Following this, an improved expression for the ray tube area is derived, and the vertical distance from the aircraft at which the ray tube area goes to zero is determined. Finally, an expression for the shock-ground intersection is obtained.

The results of the derivations show that for an accelerating, climbing flight path the effects of a positive acceleration and curvature will offset each other. Similarly, for a decelerating, diving flight path the negative acceleration and curvature offset each other. The [illegible]

-ate that undesirable focusing effects might be avoided by pitting aircraft acceleration against flight path curvature.

Lansing (see capsule summary P-43) used acoustic theory to predict the ground shock patterns resulting from maneuvering aircraft. However, his derivation did not include the effects of winds, while the present study does. Furthermore, the present theory offers an improvement over acoustic theory. However, the error in the ray tube area formula made in the earlier paper (see capsule summary P-33) means that the results obtained here are not entirely correct.

P-52
THE EFFECTS OF THE NONUNIFORM ATMOSPHERE ON THE PROPAGATION OF SONIC BOOMS
Edward J. Kane
Proceedings of the Sonic Boom Symposium, Journal of the Acoustical Society of America, Vol. 39, No. 5, Part 2, November 3, 1965, pp. S26-S30

This paper summarizes the results of an earlier investigation by Kane and Palmer (see capsule summary P-42) into the effects of a non-homogeneous atmosphere on sonic boom propagation and compares them with flight test data. The study was restricted to steady level flight in a stratified, nonhomogeneous, moving atmosphere.

The results are separated into: (1) effects on overpressure under the flight path; (2) effects on lateral distribution of shock strength; and (3) effects on the location of lateral cutoff. Generally, it was found that shock waves generated by flight at Mach numbers above 1.3 were relatively unaffected by extreme but realistic variations in meteorological properties from those in the U.S. Standard Atmosphere. However, shock waves generated during flight at Mach numbers between 1.0 and 1.3 were found to be quite sensitive to changes in atmospheric properties, especially wind. In addition, it was found that for flight at all supersonic Mach numbers, winds could cause extension of the overpressure distribution to large lateral distances from the flight track. This would not occur if the airplane altitude was above the altitude of maximum wind velocities. Comparisons of the theory with both high- and low-altitude flight-test data showed very good agreement and tended to confirm the validity of the approach.

This is a good brief summary of the very extensive investigation conducted earlier by Kane and Palmer.

P-53
SOME EFFECTS OF AIRPLANE OPERATIONS AND THE ATMOSPHERE ON SONIC BOOM SIGNATURES
Domenic J. Maglieri
Proceedings of the Sonic Boom Symposium, Journal of the Acoustical Society of America, Vol. 39, No. 5, Part 2, Nov. 3, 1965, pp. S36-S42

A review of the state of knowledge concerning the effects of the atmosphere and airplane operations on sonic boom signatures as of 1966 is presented in this paper. Flight test data obtained in previous investigations forms the basis for most of the discussion. The topics dealt with are: (1) effects of accelerated flight; (2) lateral spread patterns; (3) effects of atmospheric turbulence; and (4) probability distributions of sonic boom intensities.

The results showed that the acceleration and lateral spread phenomena were fairly well understood and predictable as of 1966. It was also shown that variations in the sonic boom signature as a result of the effects of the atmosphere can be expected during routine operations. Very similar variations in pressure signatures were noted for both fighter and bomber aircraft.

An updated version of this paper was written by Maglieri in 1967. This later paper includes flight test data from the XB-70 airplane and a discussion of the effect of slight perturbations of the aircraft motion from steady, level flight on the sonic boom intensity. It also presents a more extensive treatment of the topics discussed in the present paper. The reader is referred to capsule summary P-75 for further details of this work.

P-54
BEHAVIOR OF THE SONIC BOOM SHOCK WAVE NEAR THE SONIC CUTOFF ALTITUDE
Manfred P. Friedman and David C. Chou
NASA CR-358, Dec. 1965

A detailed description of the behavior of a sonic boom shock wave near the sonic cutoff altitude is presented in this paper. The analysis is based upon an atmosphere in which the speed of sound decreases linearly with altitude. It is assumed that the boom was caused by an aircraft in straight horizontal flight, and the effect of winds is neglected.

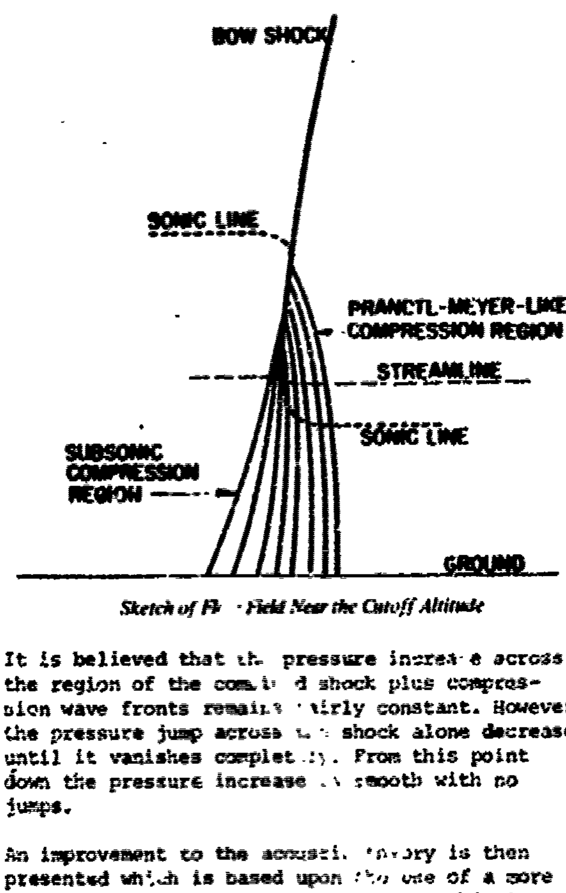
Acoustic theory is used to derive the equations for the wave fronts and rays, and these wave fronts are then used to describe the flow field. A wave front formulation, as opposed to a ray tube formulation, is used because in regions where rays approach each other and form an envelope the ray tube theory of geometric acoustics is invalid. For the present problem, the free stream sonic line is an envelope, or caustic, of those rays leaving the aircraft at an angle $\epsilon = 90^\circ - \mu$, where μ is the Mach angle and ϵ is the inclination angle of the ray to the horizontal. Oblique shock theory is used to evaluate the pressure jump across the shock in the sonic cutoff region.

The results of the analysis show that the shock at first propagates away from the aircraft in such a manner that the pressure jump across the shock decreases as it moves outward. Since the sound speed increases as the ground is approached, the shock Mach number decreases. Also, due to refractive effects, the inclination angle of the shock to the horizontal approaches 90°. As the shock moves into the higher temperature region its inclination and Mach number combine so as to cause the flow behind the shock to become subsonic, this being determined by oblique shock theory. It is shown that, although the shock Mach number is decreasing, its inclination combines with the Mach number so as to cause the pressure jump across the shock to increase. This increase is caused by the tendency of reflected disturbances to remain in the vicinity of the shock. Instead of propagating away, downstream,

they build up inducing overpressures of twice the order of those predicted by the theory of an earlier paper by Friedman, Kane, and Sigalla (see capsule summary P-33).

Farther down the shock front in the region where the flow behind the shock is subsonic, the overpressures start decreasing again since the disturbances behind the shock are again able to propagate away.

Even farther down the shock front there is a region where compression wave fronts have arrived ahead of the shock. These fronts are signals traveling along rays which have entered regions where the propagation speed is greater than the aircraft speed. There is a definite limited region, set by the ground temperature profile and the aircraft altitude and Mach number, in front of the shock where these signals can reach. The flow configuration, shown in the figure below, which was taken from this paper, is a steady one, moving with the shock at aircraft speed. The compression wave fronts, being characteristic surfaces, form a Prandtl-Meyer like compression fan and the shock ends embedded in this fan.



Sketch of Fl · Field Near the Cutoff Altitude

It is believed that th pressure increase across the region of the com d shock plus compression wave fronts remains airly constant. However, the pressure jump across t shock alone decreases until it vanishes complet y. From this point down the pressure increase is smooth with no jumps.

An improvement to the acousti. theory is then presented which is based upon the use of a more exact expression for the sound speed. This improvement leads to corrections for the shock location and cutoff altitude but they not change the general behavior of the shock already described.

None of the previously developed shock propagation theories (see capsule summaries ... P-33, for example) adequately des... low

behavior as the subsonic region behind the shock is approached. These theories do not use oblique shock relations. They consider a shock propagating down a ray tube with the shock front normal to the sides of the tube and hence use normal shock relations. For this approach the condition of flow behind the shock; i.e., whether it is subsonic or supersonic, is disregarded. Whitham's original paper (see capsule summary G-3) requires supersonic flow everywhere, since that theory is based on properly locating the characteristics. The ray tube theories, since they do not explicitly consider the shock angle, cannot completely describe some of the flow properties obtained by the oblique shock approach. These theories are valid when the flow behind the shock is either subsonic or supersonic, but not for a region where the flow behind the shock approaches Mach 1.

This was the first in-depth investigation of shock wave behavior in the vicinity of cut-off. It contains what appears to be a correct description of the phenomena that occur below shock wave cut-off, but the estimates of pressure magnitude are incorrect because second order effects have been ignored. Seebass (see capsule summary P-145) has made an attempt to describe the pressure variation by taking nonlinear effects into account, and Haglund and Kane (see capsule summary P-162) present experimental data in the vicinity of shock cut-off.

P-55
THEORETICAL STUDY OF THE PROPAGATION OF SOUND. APPLICATION TO ANTICIPATION OF THE SO IC BOOM PRODUCED BY SUPERSONIC FLIGHT
Jean-Pierre Guiraud
NASA TTF-387, Dec. 1965

This 332 page volume consists of the "Course Notes" of the Course on Higher Aerodynamics taught by the author at the Henri-Poincare Institute (Theoretical Mechanics). In these notes the mathematical theories of acoustics are applied to the propagation of plane, circular, and multidimensional sound waves in homogeneous and inhomogeneous media in motion and at rest. The Mach wave train of a supersonic aircraft in calm and moving air is calculated in detail, taking shock wave propagation and sonic boom prediction into consideration. The acoustic effect of the fuselage and of various wing planforms on the ambient air, as a function of the laws of thickness and stress, is calculated. The sonic boom is calculated, with allowance made for dissipation phenomena.

As stated by the author, these notes were hastily assembled, with entire disregard of presentation. Furthermore, the basic aim of producing a sufficiently ample document in as short a time as possible did not permit careful editing. In spite of its shortcomings, however, this is a very thorough work covering all aspects of sound propagation.

P-56
ATMOSPHERIC TURBULENCE AND THE SONIC BOOM
Thomas Y. Palmer
Boeing Company Document No. ' -16316TN,
Dec. 1965

The effect of turbulent temperature and wind fields on the characteristics of measured sonic boom signatures is investigated in this paper. The mathematical theory describing the turbulence and its interaction with an N-wave is briefly outlined.

Results of a statistical analysis of data from the 1964 Oklahoma City Sonic Boom tests indicate that the occurrence of anomalous overpressures is a function of the low level wind speed and direction and the vertical temperature lapse rate. A nomograph developed for finding the maximum expected value of overpressure indicates that the maximum anomalous overpressure (as well as minimum values) can be expected when the wind speed is about 14 knots and the temperature lapse rate is twice the adiabatic lapse rate of 1°C/100 meters. It is also found that the overpressures at Oklahoma City as a function of distance and time are uncorrelated. This indicates that the scale of turbulence which affected the sonic boom was less than five miles.

In an earlier paper (see capsule summary P-42) Kane and Palmer discussed the theoretical aspects of low altitude turbulence in much greater depth than that of this paper. However, the analysis of the Oklahoma City data made in the present paper makes several points not made in the earlier paper (the ones discussed in the previous paragraph).

P-57

THE STRUCTURE OF SHOCK WAVES AT LARGE DISTANCES FROM BODIES TRAVELING AT HIGH SPEEDS

G. M. Lilley

From Extrait des rapports du 5^e Congres International d' Acoustique, Vol. II: Conferences Generales, Liege, 1965, pp. 109-162

The purpose of this paper is to review sonic boom theory as of 1965, with the emphasis on the acoustic theory of shock propagation together with its correction for non-linear effects. Whitham's theory is reviewed first and is extended to allow for non-homogeneities in the atmosphere. In the case of a non-homogeneous atmosphere without wind it is shown that the effect of the density gradient is to increase the amplitude of the disturbance by ρ/ρ_o with the waveform unchanged, where ρ is the undisturbed density and ρ_o is the undisturbed density at the aircraft altitude. For a general atmosphere no simple expression is found for the atmospheric amplification factor and it is shown that special attention needs to be taken to find the true curvature of the wave and not only its change in slope as a result of wind and temperature gradients.

The correction to linear theory is then discussed. This correction is based upon Whitham's assumption (see capsule summary G-3) that linear theory gives the correct value for the pressure perturbation but the value is located on the wrong characteristic. However, the correction here is made for a non-homogeneous atmosphere. The location and inclination of the shock wave in this atmosphere is then investigated using the Rankine-Hugoniot shock relations and the "angle property", which states that the shock bisects the Mach directions upstream and downstream of it.

The theories of Rao and Walkden (see capsule summaries P-11 and G-6, respectively) concerning unsteady motion and the shock wave pattern for bodies with volume and lift, respectively, are reviewed briefly. The paper concludes with some brief comments on the effects of heat conduction and viscosity on the shock wave structure.

It is pointed out by the author that most previous theories (see, for example, capsule summary P-35) neglected the effect of wave curvature on the pressure perturbation. These theories include the effects of ray refraction, but the correction of the characteristics to account for atmospheric inhomogeneities is not made. Hayes (see capsule summary P-98) does make this correction.

This is a good brief review of sonic boom theory as of 1965.

P-58

SONIC BANG INTENSITIES IN A STRATIFIED, STILL ATMOSPHERE

D. G. Randall

Royal Aircraft Establishment Technical Report No. 66002, Jan. 1966

In this paper results are obtained for the sonic boom intensity of an airplane in steady, level flight in an atmosphere where the speed of sound decreases linearly from the ground to a certain altitude and then stays constant. These results are obtained by a combination of geometrical acoustics and a modification of linear theory to take account of non-linear effects.

The ray equations are derived from Fermat's principle, which states that the path taken by a disturbance traveling between two points in an inhomogeneous atmosphere is the one which requires the least time. The time taken for a disturbance moving at the speed of sound to travel down the ray to a given point is then determined.

A formula corresponding to Whitham's equation for the asymptotic pressure rise across the bow shock in a homogeneous atmosphere (see capsule summary G-3) is derived for a stratified atmosphere. An application is then made to a representative atmosphere. The results show that the non-homogeneity of the atmosphere has two effects on the sonic boom intensity. The first, and main, effect is the increase in intensity caused by the convergence of the rays. The second effect is the change caused by the variation in atmospheric pressure.

In an earlier paper Lansing (see capsule summary P-43) derived the ray equations for an atmosphere having a linear temperature gradient in a manner similar to that of this paper. However, Lansing was concerned only with the ground pattern of the sonic boom, and he did not correct the intensity of the sonic boom to account for the effects of a non-homogeneous

atmosphere. The present paper is very similar to an earlier paper by Warren (see capsule summary P-41).

This is a very clear, well presented paper. However, the neglect of the effect of atmospheric winds severely limits the usefulness of the equations developed here. An additional limitation is that only the asymptotic pressure wave is considered, and the aging of an actual signature is not described.

P-59
FOCUSSING OF SUPERSONIC DISTURBANCES GENERATED BY A SLENDER BODY IN A NON-HOMOGENEOUS MEDIUM
Michael K. Myers and Morton B. Friedman
Columbia University, Department of Civil Engineering and Engineering Mechanics,
Technical Report No. 40, June 1966

The purpose of this report is to analyze the flow past a slender body of revolution moving at supersonic velocity in an atmosphere in which the speed of sound decreases linearly with altitude. Linear theory is used, and the primary interest is directed to the pressure distribution occurring in regions where the signal generated by the body is focussed by refraction. The justification for using linear theory is Whitham's hypothesis (see capsule summary G- ', which states that linear theory describes the field correctly but assigns its values to the wrong location. Hence, the authors state, under such a hypothesis in the case of variable sound speed, since the shock must vanish at the cusp, it is expected that the values of pressure predicted in the linearized theory are significant regardless of the fact that the complete shock system is not predicted above the cusp.

Using linear theory, expressions are derived for the pressure signature in the focus region for two typical bodies of revolution. It is found that the pressure rise behind the Mach surface in the variable medium is of the order of four times that occurring behind the Mach cone in a uniform atmosphere.

In an earlier paper (see capsule summary P-54), M. P. Friedman and Chou also investigated the behavior of the shock wave near the sonic cutoff altitude. However, they used oblique shock theory to find the shock strength in the neighborhood of the cusp, rather than the linear theory used in the present paper.

In a later paper Hayes developed a theory which took into account the nonlinearities at a caustic (see capsule summary P-91), and Seebass later expanded upon that theory (see capsule summary P-145).

P-60
EXPERIMENTS ON THE EFFECTS OF ATMOSPHERIC REFRACTION AND AIRPLANE ACCELERATIONS ON SONIC-BOOM GROUND PRESSURE PATTERNS
Domenic J. Maglieri, David A. Hilton, and Norman J. McLeod
NASA TN D-3520, July 1966

Results are presented in this paper of flight test measurements made at Edwards Air Force Base of the pressure signatures of a fighter airplane. The purpose of this investigation was to better define the effects of airplane operation and atmospheric refraction effects on the ground-exposure patterns. Based on the results obtained, the following conclusions were reached:

1. The sonic boom pressures, as predicted by theory, were highest on the track and generally decreased with increasing lateral distance out to the point of cutoff due to atmospheric refraction effects.

2. N-type signatures were generally observed at distances up to the calculated lateral cutoff distance. Beyond the calculated lateral cutoff distance, the signatures lost their identity, and disturbances in the form of very low rumbles were observed at distances up to about 15 miles in excess of the calculated lateral cutoff distance.

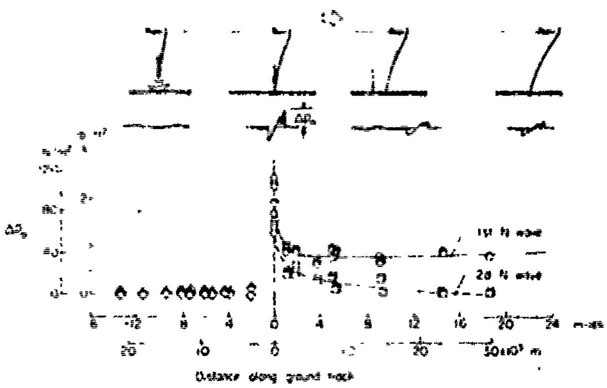
3. These disturbances or rumbles were believed to be the result of acoustic phenomena associated with the extremities of the shock waves.

4. There was a suggestion of pressure buildups due to the grazing condition during the test at cutoff Mach number along the ground track. However, because of the relatively low ground reflection factor for this condition the resulting ground overpressure values were of the same order of magnitude as those predicted for steady-level flight at higher Mach numbers.

5. For the conditions of Mach number, and altitude above cutoff, definite shock-wave signatures were observed whereas for conditions of Mach number and altitude less than cutoff the signatures lose their characteristic shape. Acoustic disturbances similar to those observed at the extremities of the lateral-spread pattern were measured.

6. Pressure buildups during acceleration from subsonic to supersonic speeds were measured in the very localized superboom region, and these buildups were noted to be up to about 2.5 times the pressures measured in the accompanying multiple-boom region (see figure below).

7. The multiple-boom region covered a distance of about 20 miles along the airplane ground track and was characterized by two N-waves producing four booms. The highest pressures were associated with the first N-wave to arrive in each case (see figure below), and these were of the same order of magnitude as would be predicted for similar steady-level flight conditions.



Measured Overpressures for Three Longitudinal Acceleration Passes at M = 0.9 to 1.5

8. The locations of the superboom and multiple-boom regions were predictable to within 5 miles, provided the airplane flight profile and acceleration rate were known.

9. For the acceleration studies, disturbances in the form of rumbles were observed for large distances along the airplane ground track prior to the intersection of the shock waves with the ground. These rumbles were also believed to be the result of acoustic disturbances similar to those observed at the extremities of the lateral-spread pattern and for the cutoff Mach number flights.

The various theoretical methods available at the time this paper was written for predicting the ground pressures during accelerated airplane flight and for the lateral spread pattern during steady level flight (see capsule summaries P-37, P-43, and P-47, for example) had been verified to a certain extent in previous experimental studies (see capsule summaries P-30, P-34, and P-48). Little experimental information existed, however, in regard to detailed measurements of the sonic boom ground pressures in the multiple-boom region due to acceleration and at the extremities of the lateral spread pattern for steady level flight. The significance of this paper lies in the experimental verification of the accuracy of geometric acoustics for predicting both caustic locations and locations of lateral cutoff.

P-61
STATISTICAL MAGNIFICATIONS OF SONIC BOOMS BY THE ATMOSPHERE
Robert Dressler and Nils Fredholm
The Aeronautical Research Institute of Sweden, FFA Report 104, 1966

The statistical scatter in sonic boom overpressure due to large-scale variations in atmospheric wind and temperature for steady state cruise is investigated in this paper. The overpressure variation investigated here is not due to a "spiking" or "rounding" of the N-waves but rather to a change in ray tube area caused by the atmospheric effects. Use of linear theory to calculate the overpressure magnification in the far field is justified by the fact that only ratios of the overpressures with and without winds are computed. The validity of using geometric acoustics to calculate the propagation of the N-wave is demonstrated using Fourier transforms of N-waves and the analogy with optics.

For cruise at M = 2.2 and 50,000 feet, a Monte Carlo analysis by computer obtains relative overpressures at ground for 480 random atmospheres. These exhibit "realistic" wind temperature statistics developed by the International Meteorological Institute in Stockholm. The program calculates each entire boom carpet, selects the maximum ΔP wherever it occurs, and computes its ratio to the peak ΔP for the Standard Atmosphere.

The calculated distribution for the overpressure magnification factor is log-normal between values 1.3 and 3.0. On the average, a ΔP-magnification at least twice the peak nominal occurs in cruise once in 110 flights, and three times occurs once in 500 flights.

The overpressure calculations in this paper use an energy conservation approach which leads to the overpressure being proportional to the ray tube area. This method somewhat overestimates overpressures because it does not take into account the aging of the pressure signature or lateral spreading of the energy.

This paper is nearly identical to an earlier paper by Dressler and Fredholm (see capsule summary P-39), except that the earlier paper does not contain a justification of the use of geometric acoustics. The reader is referred to capsule summary P-39 for further details of this work.

P-62
SONIC-BOOM MEASUREMENTS DURING BOMBER TRAINING OPERATIONS IN THE CHICAGO AREA
David A. Hilton, Vera Huckel, and Domenic J. Maglieri
NASA TN D-3655, 1966

The results of measurements made using a B-58 bomber to investigate the effects of the atmosphere on the sonic-boom pressure signatures are presented in this paper. Data are presented for various atmospheric situations ranging from quiescent to turbulent and for a wide range of surface temperatures.

The measured sonic-boom signatures were found to vary widely in both peak amplitude and signature shape because of atmospheric dynamic effects. The highest overpressures were associated with peaked signatures and the lowest overpressures with rounded-type signatures.

It was found that the wave-shape distortion or lack of distortion did not occur as a localized phenomenon but seemed to result from a general atmospheric condition which existed over a wide area at the time the tests were made. Thus when signature distortion occurred at one measuring station on the flight track, it generally occurred at all microphone locations, even though the manner in which the signatures were distorted varied markedly from one measuring point to another.

The statistical variations of the data were then investigated, and it was found that the variations of overpressures and impulses could be represented over a significant range by log normal distributions, the overpressures having a markedly wider range of variations than the impulses. Using data from previous investigations it was determined that the variations in overpressure and impulses for the longer wave lengths of the bomber airplane were only slightly less than the variations for fighter airplanes which produced shorter wave lengths.

In an earlier paper (see capsule summary P-34) Maglieri and Parrott presented the results of flight tests which also indicated a strong correlation between the peak overpressure and the type of signature measured. However, no statistical analysis was made in that paper. Maglieri and Hubbard (see capsule summary P-49) did make a statistical analysis of previous flight test data and their results were very similar to those of the present paper. The present paper treats the subject in more depth, however.

P-63
APPROXIMATE METHOD OF LOCATION OF A SONIC BOOM IN ACCELERATED MOTION OF AN AIRCRAFT
A. Tarnogrodski and E. Luczywek
Archiwum Mechaniki Stosowanej, Vol. 19, No. 3, 1967, pp. 411-420

This paper discusses the propagation of sonic booms from accelerating aircraft. The cases of negative constant and positive constant acceleration are considered, and also a case of variable acceleration. The analysis is based on the simplifying assumption that a shock wave propagates in the homogeneous atmosphere along the rays at the speed of sound. The condition of occurrence of a superboom is also discussed.

A later paper by Tarnogrodski (see capsule summary P-96) discussed sonic boom propagation from maneuvering aircraft in a temperature stratified atmosphere. However, neither that paper nor the present paper contains any new theoretical developments.

P-64
SONIC BOOMS ATTRIBUTED TO SUBSONIC FLIGHT
Raymond L. Barger
AIAA Journal, Vol. 5, No. 5, May 1967, pp. 1042-1043

This short note investigates the conditions under which a sonic boom can be produced by an airplane flying at subsonic speeds. Three situations are considered: rapid deceleration, flight in an atmosphere with a linear wind gradient, and flight in an atmosphere with a linear temperature gradient.

In the case of a linear wind gradient the condition for an envelope of the wave fronts, determined from the equation of propagation, to exist is found to be:

$$-hz/2a > 1 - M$$

where h = wind gradient, a = sound speed at flight altitude, M = Mach number, and z = vertical distance below flight altitude.

In a later comment on this paper (see capsule summary P-78) Kane points out an error in the derivation of the above result. The correct result is

$$-hz/a > 1 - M$$

In connection with transonic deceleration it is pointed out that when an airplane decelerates to a subsonic speed the nose shock detaches and propagates ahead of the airplane. A sonic boom may then be heard on the ground as the airplane passes over even though it is traveling at a subsonic speed.

In the case of a linear temperature gradient the condition for the existence of an envelope of the wave fronts is found to be:

$$a - kz \leq v$$

where k = sound speed gradient and v = flight speed.

This means that at subsonic speed an envelope might form below the flight level ($z < 0$) only in the case of a temperature inversion ($k < 0$).

P-65
SUMMARY OF VARIATIONS OF SONIC BOOM SIGNATURES RESULTING FROM ATMOSPHERIC EFFECTS
D. J. Maglieri, D. A. Hilton, and N. J. McLeod
Stanford Res. Inst.: Sonic Boom Experiments at Edwards Air Force Base; NSBEO-1-67, July 28, 1967, Annex C, Part I

This paper presents an analysis of data obtained during the 1967 sonic boom test program at Edwards Air Force Base. The topics discussed are: (1) the nature of signature shape variations; (2) propagation studies in the lower atmosphere; and (3) an evaluation of aircraft motion effects.

It was found that three basic types of signatures existed. These were peaked, normal, and rounded. A statistical analysis of the data showed that, with the exception of the highest and lowest valued points, data for a B-58 and an XB-70 generally follow a log normal distribution and the variability is about the same in each case. This led to the conclusion that the type and size of the airplane are not significant factors regarding variability. The variation in signature length was found to be about the same for points five miles off the flight track and points on the flight track, even though the signatures were longer for the off-track condition. For a B-58 at Mach 1.5 and an altitude of 31,000 feet, considerable variations in rise times were found. Rise times of less than a millisecond were commonly encountered.

Three main experiments were conducted in conjunction with the lower atmosphere propagation studies. In the first, flights were made over an instrumented range consisting of a linear microphone array on the ground and extending about 1500 feet in combination with a vertical array on an instrumented tower extending to about 250 feet above the ground surface. The generating aircraft was flown at an altitude of 35,000 feet and at a Mach number of 1.5 for a variety of weather conditions. In situations where wave form distortion was noted to exist, it was found that similar wave shapes were measured both at the ground surface and on the instrumented tower. Furthermore, the results suggested that similar types of distortion existed on a point on the ground and a point on the tower along given ray paths. This led to the conclusion that, for these particular tests, the 250 foot layer of the atmosphere near the surface of the ground did not appreciably affect the signature shape.

The second experiment concerning propagation in the lower atmosphere was performed with the aid of two airplanes of the same type which were flown at the same altitude and Mach number and on the same nominal flight track about 5 seconds apart. By means of a ground microphone array it was possible to measure sonic boom signatures which travelled along essentially the same ray path from a high altitude to the ground for a distance of approximately 15 miles but at slightly different times. The results showed that quite different wave shapes are associated with measurements at times a few seconds apart. This led to the conclusion that the integrated effects of changes in the atmospheric conditions along a given ray path may be significant even for such a small difference in time.

The third experiment relating to propagation in the lower atmosphere made use of a blimp to measure pressure signatures at an altitude of 2000 feet. For some cases, the incident signature was essentially undistorted, whereas the ground measurements and the reflected signature measurements at the airship showed evidence of distortion. This suggested that the 2000 foot surface layer of the atmosphere was responsible for all such distortion. However, some other measurements showed distortion of the incident wave, which indicated that the portion of the atmosphere above 2000 feet may be important for some cases.

To evaluate the effect of small perturbations to the aircraft flight path on measured pressure signatures a test airplane was flown both in steady level flight and "porpoising" flight over an instrumented array. The "porpoising" flight involved periodic 0.5 g normal accelerations. The results showed no significant differences for the signatures measured for the two flights, which indicated that the variations discussed previously in the paper were due mainly to atmospheric effects rather than to effects of aircraft motion.

Many of the results of this work are also discussed in a later paper by Garrick and Maglieri (see capsule summary P-81).

The test program discussed here was one of the most extensive ever conducted to experimentally study the effect of the atmosphere in producing pressure signature distortions. These results were a very significant contribution to sonic boom propagation theory.

P-66

PRELIMINARY RESULTS OF XB-70 SONIC BOOM FIELD TESTS DURING NATIONAL SONIC BOOM EVALUATION PROGRAM

D. J. Maglieri, V. Huckel, H. R. Henderson, and T. Putman

Stanford Res. Inst.: Sonic Boom Experiments at Edwards Air Force Base; NSBEO-1-67 July 28, 1967, Annex C, Part II

This write-up documents some of the physical measurement results from XB-70 sonic boom flight tests. The objectives of the flight tests were to verify the available sonic boom overpressure and signature shape prediction methods for large aircraft of the supersonic transport class and to evaluate the effects of the atmosphere on the sonic boom signatures for such a large airplane.

Data were obtained for a series of 20 flights of the XB-70 airplane for the Mach number range 1.38 to 2.94, for the altitude range from 31,000 to 72,000 feet, and for a gross weight range of about 300,000 to 420,000 pounds. The signature shape variations and associated variations in overpressures, impulses, and time durations were found to be similar in nature to those observed previously for smaller airplanes. Variability in the above quantities was markedly greater in June than in the November-January time period and was believed to be related to atmospheric effects. These results are also discussed in a later report by Garrick and Maglieri (see capsule summary P-81).

The significance of this investigation is that it showed that atmospheric effects on the signatures of large airplanes were essentially the same as for small airplanes.

P-67

METEOROLOGICAL INVESTIGATIONS

C. Roberts, W. Johnson, G. Herbert, and W. P. Hass

Stanford Res. Inst.: Sonic Boom Experiments at Edwards Air Force Base: NSBEO-1-67, July 28, 1967, Annex D

This paper presents preliminary results of an investigation of meteorological effects on sonic boom pressure signatures. This investigation was conducted by the Environmental Science Services Administration (ESSA) as part of the 1967 Edwards Air Force Base Sonic Boom Experiments.

The following preliminary conclusions were reached as a result of this investigation:

1. There is a slight indication that overpressure variability is greatest when flights are above the level of maximum wind, and least when they are below it.

2. Flights below the tropopause result in greater overpressure variability than flights above or within the tropopause, possibly because individual variations in the near-field disturbance are smoothed out in passing through the tropopause.

3. Very little effect of overall temperature departures from standard was indicated.

4. Analysis of the mean wind between aircraft and the surface indicated a fairly pronounced tendency for stronger mean winds to have a greater effect on the variability of mean observed overpressures.

P-68

ANALYSIS OF THE FORMULAE GIVING THE "RAY-TUBE-AREA" OF SONIC BOOM PROPAGATION THEORY
Elliot Eisenberg
Boeing Company Document D6-A11071-1TN, August 1967

The purpose of the work described in this document is to examine two different derivations of equations for the ray-tube-area and to outline a general procedure for the derivation of such an equation. The two derivations that are examined are those of Friedman, Kane, and Sigalla (see capsule summary P-33) and Randall (see capsule summary P-21).

As shown here, Randall's approach was to consider 4 rays designated by (ϕ, τ), $(\phi+\Delta\phi, \tau)$, $(\phi, \tau+\Delta\tau)$, and $(\phi+\Delta\phi, \tau+\Delta\tau)$. ϕ was defined as the initial angle the ray makes with the horizontal at the airplane flight altitude and τ was the time at which the ray was produced on the flight path. The 4 rays defined the edges of a conoid; where a parallel plane cut the conoid, a parallelogram was defined. The projection of this parallelogram normal to the ray τ, ϕ was the ray-tube-area.

The approach by Friedman, Kane, and Sigalla was to consider two rays only, one starting from the airplane at time τ and the other at $\tau+\Delta\tau$. The ray tube area is then taken to be proportional to zd, where d is the perpendicular distance between the two rays at some distance z below the airplane.

It is shown in the appendix that the ray-tube-area, A, appears in the equation for shock wave pressure in such a way that if one were to substitute KA for A in that equation (K being an arbitrary constant) the calculated value of the pressure would not be affected by the substitution. It follows that various equations for ray-tube-area will be equivalent, as far as the calculation of pressure is concerned, provided the ray tube areas are proportional to each other. It is also shown that the ray-tube-areas of Randall and Friedman are proportional to each other but only for the case of a homogeneous atmosphere. These two approaches could not be reconciled for the more general case.

An equation for the ray-tube-area is then derived by two approaches that were thought to be different from those of Randall and Friedman.

In these approaches 4 neighboring rays were considered as was done by Randall. In the first case the area is obtained by dropping perpendicular distances from one ray to its neighbors. In the other case, realizing that a shock wave is an envelope at a given time of disturbances produced at different times, the intersecting corner points of the shock wave and the rays were determined. From this the ray-tube-area equation is derived. It is found that both approaches are equivalent and that the equation obtained is the same as that of Randall.

Having shown that Randall's area is correct, the conceptual difference between the two approaches is discussed. It is pointed out that Randall in his derivation took into account the fact that the ray tube is not symmetric with respect to the flight path. Friedman, on the other hand, neglected the non-symmetry of the problem. It is therefore concluded that:

1. Randall's area is a more accurate description of the physical situation, and

2. The two ray-tube-areas will not, for the non-homogeneous case, be related by a constant factor.

The discussion presented in this paper of the two ray-tube-area expressions of Randall and Friedman is excellent. The finding that Friedman's ray-tube-area was in error was very significant, since his theory was in widespread use at the time this paper was written. However, for cases involving predictions of atmospheric effects on overpressure for asymptotic pressure signatures produced during steady flight the two expressions yielded results that differed numerically less than 5%.

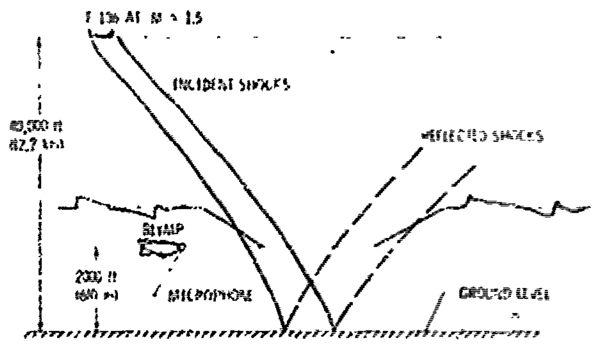
P-69

VARIABILITY OF SONIC BOOM PRESSURE SIGNATURES ASSOCIATED WITH ATMOSPHERIC CONDITIONS
I. E. Garrick and D. J. Maglieri
Paper presented at International Association of Meteorology and Atmospheric Physics, XIV General Assembly of the International Union of Geodesy and Geophysics, Lucerne, Switzerland, Sept. 25-Oct. 7, 1967

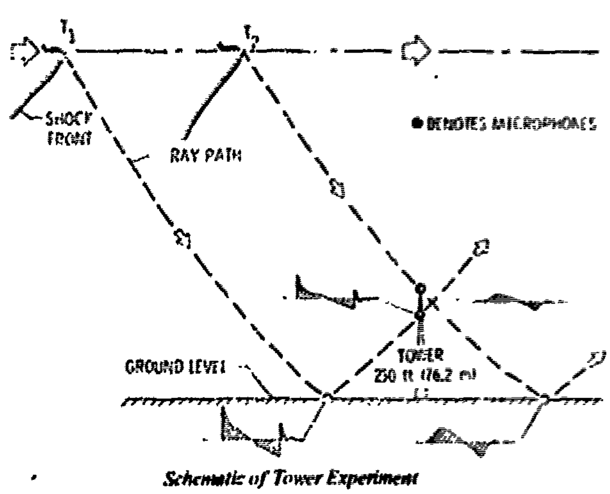
This paper presents a summary of the knowledge concerning atmospheric effects on the sonic boom as of 1967. Topics treated are: (1) effects of atmospheric turbulence on pressure signatures; (2) atmospheric effects on energy spectra of pressure signatures; (3) lateral distribution of sonic boom overpressure; and (4) a statistical analysis of sonic boom overpressures and positive impulses.

In connection with the effects of atmospheric turbulence on pressure signatures it is shown that when atmospheric conditions are unstable, the normal N-wave may become "rounded" or "spiked." The results of the two previous investigations conducted to determine the region of the atmosphere in which the modification of the pressure signatures takes place are presented. These experiments are illustrated in

the two figures below. In the first experiment, the flow field of an aircraft flying at a Mach number of 1.5 at an altitude of 40,000 feet was probed at 2000 feet by an instrumented blimp. For a number of cases, as illustrated in the figure, the incident signature was undistorted, whereas both the ground signature and reflected signature at the blimp showed distortion. This demonstrated clearly that, for these cases, the 2000 foot surface boundary layer was the effective agent. On the other hand, other measurements with the blimp indicated distortion of the incident wave itself, showing that the higher altitudes were responsible for the turbulence. The experiment illustrated in the second figure demonstrated that the atmosphere below 250 feet was not significantly modifying the pressure signature, since when wave form distortion was noted to exist, it was found that similar wave shapes occurred both at the ground surface and at the tower for both incident and reflected waves.



Schematic of Blimp Experiment



Schematic of Tower Experiment

A table, included in this paper to provide a convenient summary of some of the results of several flight programs, is shown below. Presented are the mean values measured as ratioed to the nominal values calculated. Also shown are the $\pm\sigma$, $\pm2\sigma$, and the $\pm3\sigma$ ranges of values as ratioed to the mean-to-nominal ratio.

TEST SITE	TIME PERIOD	RANGE OF MACH NO.	RANGE OF ALTITUDE, Km	MEAN OF $\Delta p_{meas}/\Delta p_{calc}$	RATIOS RELATIVE TO MEAN FOR RANGE OF $\pm1\sigma$	$\pm2\sigma$	$\pm3\sigma$	NUMBER DATA POINTS
OKLA. CITY 1	FEB.-JULY 1964	1.2 - 2.6	8.5 - 14.6	0.991	.60 - 1.38	.56 - 1.78	.49 - 2.4	549
3*				1.201	.74 - 1.51	.56 - 1.97	.49 - 2.31	[illegible]
4†				1.161	.68 - 1.49	.45 - 2.38	.34 - 3.21	544
OKLA. CITY 1	FEB.-JULY 1964	1.3 - 2.0	6.4 - 12.5	.974	.76 - 1.30	.58 - 1.8	.45 - 2.25	657
3*				1.041	.73 - 1.37	.53 - 1.96	.39 - 2.55	[illegible]
4†				.962	.67 - 1.38	.45 - 2.21	.36 - 2.38	[illegible]
EDWARDS AFB	NOV.-JAN. 1966-67	1.5	[illegible]	[illegible]	.76 - 1.72	.61 - 1.64	.47 - 2.11	[illegible]
CHICAGO	JAN.-MAR. 1965	1.2 - 1.86	11.6 - 15.6	.92	.77 - 1.29	.60 - 1.62	.46 - 2.15	[illegible]
EDWARDS AFB	SEPT.-OCT. 1961	1.5 - 2.0	9.4 - 21.3	1.05	.90 - 1.11	.81 - 1.21	[illegible]	[illegible]
COMBINED		1.2 - 2.5	9.4 - 21.9	.90	.80 - 1.24	.65 - 1.5	.54 - 1.82	[illegible]
EDWARDS AFB	NOV.-JAN. 1966-67	1.5 - 2.5	11.3 - 18.[illegible]	1.00	.81 - 1.20	.82 - 1.2	[illegible]	[illegible]
EDWARDS AFB	NOV.-JAN. 1966-67	3.0	21.[illegible]	.96	.86 - 1.36	.75 - 1.38	.64 - 1.56	[illegible]

*5-MILE OFFSET FROM FLIGHT TRACK
†10-MILE OFFSET FROM FLIGHT TRACK
NOMINALS CALCULATED FOR ISOTHERMAL ATMOSPHERE
OTHER NOMINALS CALCULATED FOR STANDARD ATMOSPHERE

Statistical Variations of Peak Overpressures

The statistical analysis of overpressure measurements indicates that the pressure peaks and impulses follow approximately a log normal probability curve. It is also shown that the variability of the data is very similar for fighters and bombers.

A comparison of the energy spectra of a "spiked" signature and a "rounded" signature showed that only relatively small differences existed in the envelopes of the amplitudes, despite the large difference in signatures and maximum overpressures. The lower frequencies of the spectra were well correlated, while for the higher frequencies there are indications that the relative phases of the two waves tend to become random.

This paper is very similar to but more extensive than an earlier paper by Maglieri (see capsule summary P-75). The reader is referred to that capsule summary for a further discussion of these results. All of the material contained in this paper is also contained in a later NASA technical note (see capsule summary P-81).

P-79

THE EFFECT OF ATMOSPHERIC NONUNIFORMITY ON SONIC BOOM INTENSITIES

Ryuma Kawamura and Mitsuo Makino
Institute of Space and Aeronautical Science, University of Tokyo, Report No. 416, Vol. 32, No. 9, Oct. 1967, pp. 191-213

A theoretical investigation of the effects of a non-homogeneous atmosphere on sonic boom propagation for the case of steady level flight is presented in this paper. First an analysis is made for an axisymmetric body in an adiabatic atmosphere, together with the two-dimensional body case. The decay of a bow shock due to atmospheric nonuniformity is obtained by the application of Whitham's theory (see capsule summary G-3) to the case of a stratified atmosphere. Numerical calculations are carried out at flight Mach numbers from 1.3 to 3.0 and flight altitudes up to 10 km.

Extension of the above technique is used to obtain the decay of a bow shock in an arbitrary stratified atmosphere. A numerical calculation is made of the ratio for the case of an axisymmetric body

in a standard atmosphere at the same flight Mach numbers as above and flight altitudes up to 20 km. The results are compared with those of Friedman, Kane, and Sigalla (see capsule summary P-33), whose calculations were based upon the ray tube method. The ray tube method rests on the basic assumption that the propagation of the disturbance down each tube may be treated separately, whereas Whitham's theory, upon which the method of the present paper is based, involves disturbances propagating along the shock front. However, good agreement was obtained between the two approaches, the largest difference being about 5%.

This paper, by deriving the atmospheric correction factor by an independent method, demonstrated the essential validity of the results of Friedman, Kane, and Sigalla for the effect of the atmosphere on the bow shock of an asymptotic pressure signature.

P-71
LINEAR THEORY OF SUPERBOOMS GENERATED BY REFRACTION
M. K. Myers and M. B. Friedman
Journal of Aircraft, Vol. 4, No. 6, Nov.-Dec. 1967, pp. 486-493

This paper analyzes the flow past a slender body of revolution moving at supersonic velocity in an atmosphere in which the speed of sound decreases linearly with altitude. Linear theory is used, and the primary interest is directed to the pressure distribution occurring in regions where the signal generated by the body is focused by refraction.

This paper is virtually the same as an earlier report by Myers and Friedman (see capsule summary P-59). The reader is referred to the capsule summary of that paper for details of this work.

P-72
REPORT ON MEASUREMENTS OF SONIC BANGS DURING EXERCISE SUMMER SKY
M. E. Delany, D. R. Johnson, D. P. Pernet, and A. J. Rennie
National Physical Laboratory Special Report 005, A.R.C. 29 762, Dec. 1967

Measurements of sonic booms resulting from flights of a lightning aircraft over London at Mach 1.4 are presented in this paper. Measurements were made both at ground level and at elevated points. This system permitted the inclination angle of the incident shock wave to be determined. It also made it possible to identify not only the primary reflection from neighboring buildings but also, in the case of the elevated microphones, the wave which had been successively reflected first from a nearby building and then from the ground.

The ratio of the amplitude of the shock wave reflected from the ground to that incident on the ground was found to be highly variable, ranging from 0.19 to 2.4. No systematic difference was observed between reflection from grass and reflection from gravel.

A close similarity was found, in most cases, between the front and rear shocks in a given pressure signature. It is noted that such similarity between front and rear shocks is consistent with the hypothesis that deviation from idealized N-type configuration is due to atmospheric turbulence in the lower atmosphere - both shocks necessarily traversing almost identical paths through the atmosphere.

Values of time delay between the arrival of incident and reflected waves were calculated both for the ground stations and elevated stations using the direction consines of the wave normal. The comparison between these calculated values and the measured values was good.

The measured pressure signatures of the shock waves reflected from a nearby building showed a loss of low-frequency components. It is noted that some loss of low frequencies is to be expected when shocks are reflected from a plane surface whose physical dimensions are not very large compared with the wavelength in air of the lowest frequency components. It is also pointed out, however, that this is not an entirely satisfactory explanation, since similar spiky reflection patterns were occasionally observed from ground reflection.

Lansing's acoustic method was used to calculate ground intersection patterns and wave-normal angles. Qualitative agreement was found with measured values.

This investigation did not produce any results which had not already been determined from previous flight-test investigations. It did, however, substantiate many previous findings.

P-73
BRIEF REVIEW OF THE BASIC THEORY
Wallace D. Hayes
NASA SP-147, 1967, pp. 3-7

This review divides sonic boom theory into five areas, corresponding to the calculations required: (1) for the local flow field near the aircraft and the associated asymptotic disturbance far from the aircraft; (2) for the tracing of a sound ray through a non-uniform atmosphere with winds; (3) for the calculation of the area of a ray tube as it varies along a ray; (4) for the calculation of an "age" variable (see capsule summary P-98); and (5) the use of an age variable in obtaining the signature after its distortion due to nonlinear effects. The appropriate theory for each of these areas is briefly reviewed.

The theory is summed up as being a composite one, involving a local theory near the aircraft, a geometric acoustics theory, and a nonlinear distortion theory. The principal assumptions of the theory are those of geometric acoustics--that the characteristic scale and time of the signature are small compared with the atmospheric scale height and wave front radius of curvature and with various natural periods of the atmosphere. It is pointed out that the theory fails completely near a caustic and near a "shadow" or "cutoff" point, where rays are tangent to the ground.

Certain minimization concepts are then discussed. For discussion of these see capsule summary H-20.

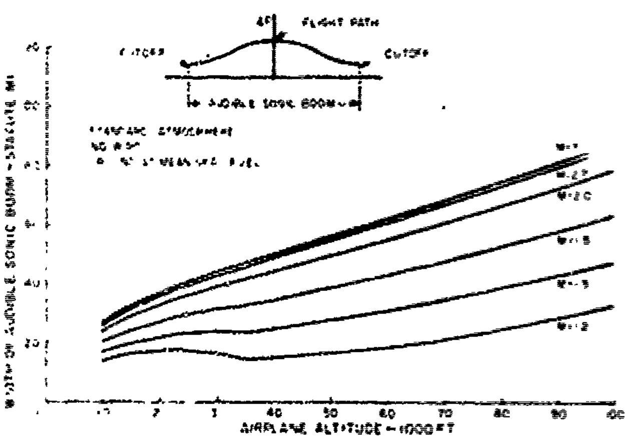
This is a good concise summary of the state of the art of sonic boom propagation theory as of 1967.

P-74
SOME EFFECTS OF THE ATMOSPHERE ON SONIC BOOM
Edward J. Kane
NASA SP-147, 1967, pp. 49-63

This paper presents a brief summary of the knowledge of atmospheric influence on the sonic boom as of 1967. The topics discussed are: (1) the scaling of the bow shock overpressure to account for atmospheric effects; (2) the effect of the atmosphere on the lateral distribution and extent of sonic boom at the ground; (3) shock waves which just reach or "graze" the ground; and (4) the distortion of pressure signatures by atmospheric turbulence.

The scaling of the bow shock overpressure of an asymptotic pressure signature to account for atmospheric effects is accomplished through the use of an atmospheric correction factor, K_A (see capsule summary P-42). This factor can be used when atmospheric conditions approximate those of the U.S. Standard Atmosphere, 1962. It is a function of airplane Mach number and flight altitude. For variations from standard day conditions the maximum variation in predicted overpressure is about 5 percent for steady flight at Mach numbers above 1.3. For flight Mach numbers between 1.0 and 1.3, larger variations are predicted. The shock waves are approaching a "grazing" condition in this Mach number range which appears to offset this increase in variation.

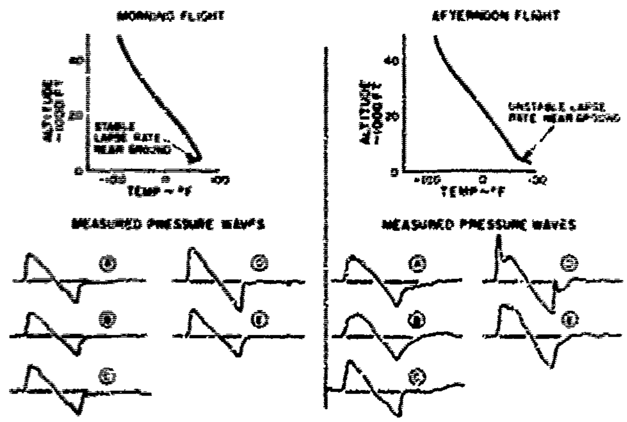
The effect of the atmosphere on the lateral distribution and extent of the sonic boom at the ground for Standard Atmosphere conditions is summarized by the figure below, which was originally presented in an earlier paper by Kane and Palmer (see capsule summary P-42)



Width of Audible Sonic Boom on Ground

When the airplane is flying at a Mach number such that the shock waves will just reach or "graze" the ground under the airplane, it is said to be flying at the threshold Mach number. A discussion of the overpressure on the ground for this flight condition is presented.

The effect of atmospheric turbulence on pressure signatures is shown in the figure below. This figure shows that pressure signatures measured early in the morning when conditions near the ground were generally stable are nearly identical and resemble N-waves. Signatures obtained in the afternoon when the lapse rate near the ground was generally superadiabatic show a wide variation in shape and maximum overpressure even though they were produced at nearly the same flight conditions as the earlier data. This indicates that pressure signature distortions are the result of interactions between local turbulence near the ground and incoming shock waves. It is then pointed out that no analytical description of this phenomenon was available at that time.



Effect of Turbulence on Signature Shape

The appendix gives a brief review of the theory developed in an earlier paper by Friedman, Kane, and Sigalla (see capsule summary P-33).

Most of the material presented in this paper is drawn from an earlier paper by Kane and Palmer (see capsule summary P-42). The important concepts of that paper are summarized very concisely in the present paper together with the presentation of experimental data obtained after the earlier paper was written.

P-75
SONIC BOOM FLIGHT RESEARCH--SOME EFFECTS OF AIRPLANE OPERATIONS AND THE ATMOSPHERE ON SONIC BOOM SIGNATURES
Domenic J. Maglieri
NASA SP-147, 1967, pp. 25-48

This paper presents a review of the state of knowledge concerning the effects of the atmosphere and airplane operations on sonic boom signatures as of 1967. The discussion centers mainly around previously obtained flight test data. The topics discussed are: (1) effects of accelerated flight; (2) lateral-spread patterns; (3) effects of atmospheric turbulence; (4) the effect of slight variations of the aircraft motion from steady, level flight; and (5) probability distributions of sonic boom intensities.

The discussion of the effects of accelerated flight and lateral spread parallels that of an earlier paper by Maglieri, Hilton, and McLeod (see capsule summary P-60). The only difference is that the present paper presents data showning the lateral spread pattern of the XB-70. It is concluded from the data presented that the acceleration and lateral-spread phenomena appear to be fairly well understood and predictable.

The data concerning the effects of atmospheric turbulence on the pressure signature indicate that the portion of the atmosphere below 2000 feet is the most influential, although in some cases the higher portions may also be important. Very

similar variations in pressure signatures were noted for small, medium, and large aircraft.

Aircraft motions, in the form of perturbations about the normal flight track, are shown not to contribute significantly to observed sonic boom signature variations. This is taken as evidence that the variations discussed previously in the paper are due mainly to atmospheric effects rather than to effects of aircraft motion.

A statistical analysis of the variations in overpressure and positive impulse showed: (1) the impulse data generally had less variability than the overpressure data; (2) the variation in overpressures for a medium size airplane was found to be only slightly less than for a small airplane; (3) the amount of variation was less for data measured during the winter months than for data measured during the summer months (believed to be a result of the more stable atmosphere during the winter due in part to the reduced convective heating in the lower layers); and (4) the probability distribution for measurements obtained at distances out to 13 miles shows larger variability than for measurements on the flight track (believed to be due to the longer ray paths travelled by the waves in the lower layers of the atmosphere in order to reach the lateral stations).

This paper does a good job of summarizing the results of those portions of previous investigations concerned with the effects of the atmosphere and aircraft maneuvers on the sonic boom.

P-76
NONLINEAR PROBLEMS IN WAVE PROPAGATION
Klaus Oswatitsch
Space Science Seminar, George C. Marshall Space Flight Center, Report No. SSS-67-74, 1967

A method for the theoretical prediction of weak shocks and Prandtl-Meyer expansions in unsteady flow or in three-dimensional steady supersonic flow is presented in this report. The method developed is an analytical characteristic theory for small disturbances. As in all characteristic theories the flow properties, such as velocity components and pressure, are dependent variables depending on certain characteristic independent variables. The coordinates, and in unsteady flow the time, are also dependent variables. Thus, while acoustic theory allows only the physical flow quantities such as the pressure and velocity to be perturbed, the analytical method of characteristics also allows perturbations of the coordinates.

In this theory, rather than working in the physical space as in the acoustical theory, a characteristic space in which the Mach lines are exact straight lines is used. Plane Mach surfaces and exact circular Mach cones can be introduced, and the initial and boundary conditions of the characteristic space must be introduced. After the problem has been solved in the characteristic space, the location of the characteristic independent variables in the physical plane must be found by integrating equations derived which express the relationship, between the first order disturbances of the coordinates, the first order disturbances of the velocity components, and the independent characteristic variables.

The translation of the boundary and initial conditions from the physical space to the characteristic space is easy in those cases where the acoustical theory gives good results near the body. In cases where the acoustical theory gives wrong or no results near the body, the translation of the boundary conditions can cause difficulties, and several problems still are not solved. However, one of the solved problems is the solution of the flow field about a delta wing with sonic leading edges. The solution of the flow field around various delta wings with sonic or near-sonic leading edges is then illustrated.

In later papers (see capsule summaries G-49 and G-72) Oswatitsch and Sun use the analytical method of characteristics to investigate the sonic boom of a delta wing.

The presentation of the theory in this paper is excellent. The derivations are concise and straightforward with many well-chosen illustrations.

P-77
THE EFFECTS OF WINDS AND INHOMOGENEOUS ATMOSPHERE ON SONIC BOOMS
Y. S. Pan
New York University--AA-68-1, January 1968

This paper presents a study of the effects of winds and inhomogeneous atmosphere on sonic booms by use of a shock wave-vortex sheet interaction concept. The atmosphere is assumed to be inviscid, non-conducting and constituted by a finite number of parallel horizontal streams. Disturbances generated by a supersonic aircraft propagating through the atmosphere are reflected and transmitted at each interface between two streams. The last transmitted disturbance striking the ground is reflected regularly.

By using this model it is found that the shape of the disturbance remains undistorted, and that its strength and propagation direction change as it propagates through different streams. The overpressure of a disturbance on the ground can be represented by the overpressure of the same disturbance passing through a homogeneous stream multiplied by a "modification factor" K_n:

$$K_n = 2^{n-1} / \prod_{i=2}^{n} \left(1 + \frac{\mu_{i-1}}{\mu_i}\right)$$

where $\mu_i = M_i^2 \left(M_i^2 - 1\right)^{1/2}$ and M_i is the Mach number of the i^{th} stream.

Propagation for a simple weak shock and an N-wave disturbance through three parallel streams is carried out. Results show that the location of the disturbance on the ground depends on the stream thicknesses and Mach numbers, and the strength on the ground depends only on the stream Mach numbers. It is shown that if the Mach number of the lowest stream near the ground is equal to or less than that of the first stream, the strength of the disturbance is always reduced. This conclusion is generalized to sonic booms propagating through an atmosphere constituted by a finite number of streams.

In connection with the sonic boom experiments carried out at Edwards Air Force Base in 1967, it is shown that the findings of those experiments are consistent with the results of the present analysis. It is pointed out that the difference in the wave shapes observed in that experiment on the ground and generated by two F-106 airplanes flying at the same altitude and Mach number and on the same nominal flight track about 5 seconds apart may be due to the fact that the second plane was flying at a slightly different Mach number from the first plane because of the wake behind the first plane and the reflected disturbances from the first plane. Consequently, based on the analysis of this paper, the sonic boom signatures may be different.

Friedman, Kane, and Sigalla (see capsule summary P-33) presented a very complete treatment of a shock propagating through an atmosphere with temperature, pressure, and wind variations. The purpose of the present paper was to present a simpler model in which the computational difficulties due to the interdependence among shock strength, location and ray tube area in the former method do not arise. It should be noted that the method of the present paper scales only the magnitude of the N-wave overpressures, just as Friedman, Kane, and Sigalla did, and does not account for changes in signature shape as it propagates away from the airplane.

P-78
COMMENT ON "SONIC BOOM ATTRIBUTED TO SUBSONIC FLIGHT"
E. J. Kane
AIAA Journal, Vol. 6, No. 2, February 1968, p. 379

This short note presents a correction to an expression derived by Barger in an earlier paper (see capsule summary P-64) giving the condition for a shock wave to form due to the flight of an airplane in an atmosphere having a linear wind gradient. The expression derived by Barger is:

$$-hz/2a > 1 - M$$

where h = wind gradient
z = vertical distance below flight altitude
a = sound speed at flight altitude and
M = airplane Mach number

In checking the results Kane found that the inequality was in error by a factor of 2. The error stemmed from the failure to substitute the expression for cos γ, which is a function of z, into the expression for $d(\Delta x)/dz$ before integrating with respect to z. The correct result is

$$-hz/a > 1 - M.$$

P-79
DISTORTION OF SONIC BANGS BY ATMOSPHERIC TURBULENCE
S. Crow
National Physical Laboratory Aero Report 1260, A.R.C. 30 009, March 11, 1968. (Also see J. Fluid Mech., Vol. 37, p. 529, 1969)

The purpose of this paper is to present a theory which explains the experimentally observed fine structure of an N-wave which has been distorted by atmospheric turbulence. The following five experimentally observed characteristics are used as clues to the origin of the experimentally observed fine structure:

(1) Perturbations from the basic N-shape are random.

(2) The amplitude of the pressure perturbation at the leading or trailing shock tends to be large, often comparable to the pressure jump that would have occurred across an undeformed shock. The amplitude of the perturbations decreases rapidly behind the shock.

(3) The duration of the spike behind a shock is very short, say 5-30 ms, corresponding to a length scale in the incident pressure wave of 5-30 feet. The duration and length scale of the spikes increase steadily behind the shock, but the duration of a spike is never more than a small fraction of the total duration of the N-wave.

(4) The perturbations associated with the leading shock are exactly the same as those associated with the trailing shock.

(5) In pressure signatures measured at elevated stations, the perturbations associated with the leading and trailing shocks of the incident wave are the same. The perturbations associated with the two shocks of the reflected wave are also the same as each other, but they often bear little resemblance to the perturbations associated with the incident N-wave.

Acoustic scattering theory, studied by Lighthill (see capsule summary P-6), Batchelor (see capsule summary P-15), and others is applied to explain the five attributes listed above. The turbulence is assumed to be concentrated near the ground in a boundary layer of thickness much less than the altitude of the airplane and also much less than the scale height of the atmosphere.

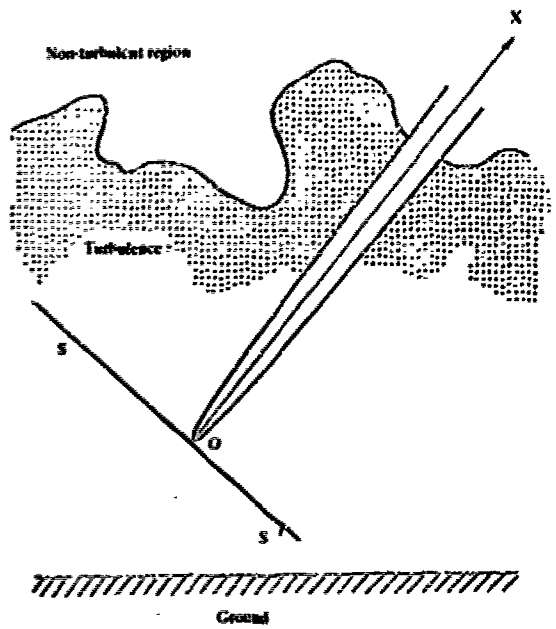
Two kinds of scattering, inertial scattering and thermal scattering, are treated. The equations for inertial and thermal scattering are derived separately from the continuity and momentum equations, and then combined into a comprehensive scattering equation under the assumption that the scattered waves are a small perturbation on the incident wave.

Inertial scattering is the generation of acoustic waves by the interaction of sound and turbulence. As an N-wave passes a turbulent eddy, it causes a change in the local momentum flux and consequently a change in the local pressure. The pressure change then radiates away as an acoustic wave.

The essential idea underlying thermal scattering is that the heated fluid is free to expand so that the density and the speed of sound are affected but not the pressure. Fluctuations in the velocity and pressure are therefore associated strictly with the acoustic wave, whereas fluctuations in density and the speed of sound are caused almost entirely by the temperature inhomogeneities.

In connection with an incident plane wave it is shown that the only component of turbulent velocity that contributes to scattering is the one normal to the shock and that normal velocity fluctuations and thermal fluctuations scatter in exactly the same manner in a perfect gas. It is also shown that inertial scattering is more important than thermal scattering.

The first topic treated is scattering from a weak shock. An exact solution of the scattering equation is derived which is finite at the shock and everywhere behind it. This solution is in the form of a surface integral over a paraboloid of dependence whose focus is the observation point and whose directrix is the shock. A sketch of the paraboloid of dependence which was taken from this paper is shown below. In this figure O is the point of the observer and S S' is the shock. The solution is found to degenerate at the shock into the result given by ray acoustics.



Paraboloid of Dependence

The prediction of the scattering theory is then checked to see if it explains the five characteristics of the N-wave perturbations listed earlier. The following qualitative explanations are arrived at using this theory, the numbers corresponding to the numbers given earlier:

(1) The perturbations are random because the mean temperature and velocity fields merely focus or defocus the N-wave uniformly.

(2) The perturbations are large because a large number of individually weak interactions contribute to the scattered wave. Individual interactions are small but their sum is large. The perturbations decrease with time after the passage of the shock because the interaction is weighted with a factor that approaches infinity as the distance between the observer and the shock approaches zero.

(3) The length scale of the perturbations is small because a small change in the distance between the observer and the shock brings about a much larger change in the position of the surface of the paraboloid of dependence. The fine structure of an N-wave is a highly compressed and distorted image of the turbulence that the wave has encountered.

(4) The leading and trailing shocks share a common fine structure because the scattered waves that arrive at a fixed observation point at a given time after the passage of the trailing shock come from the same paraboloid of dependence as those waves that arrived a similar time after the passage of the leading shock. The two paraboloids are separated by the passage time of the N-wave, but this time is not enough for the wind to carry eddies a significant distance through the surface of a given paraboloid.

(5) A microphone on a tower records different spikes behind incident and reflected shocks because the corresponding paraboloids of dependence do not coincide. This is because the paraboloid of dependence reflects from the ground just as the shock does.

The analysis then becomes more quantitative, and it is shown that the main sources of pressure signature spikes are eddies in the Kolmogoroff inertial subrange. It is also shown that, for almost all separations, h, between the shock and the observation point, the mean square pressure perturbation equals $(\Delta p)^2 (h_c/h)^{7/6}$, where Δp is the pressure jump across the shock and h_c is a critical distance predicted in terms of meteorological conditions. Finally, a frequency analysis shows that scattering can considerably augment the psychological impact of a sonic boom.

The theory of the present paper was qualitatively substantiated in later investigations by Bauer and Bagley (see capsule summary P-113) and by Kamali and Pierce (see capsule summary P-133).

This is a very significant paper in the development of sonic boom propagation theory. It goes far beyond all previous papers in showing how the fine structure of distorted N-waves can be explained by acoustic scattering theory.

P-80
SPIKES ON SONIC-BOOM PRESSURE WAVEFORMS
Allan D. Pierce
Journal of the Acoustical Society of America, Vol. 44, No. 4, 1968, pp. 1052-1061

A mechanism is presented in this paper which interprets the spikes on sonic boom pressure signatures as being due to the simultaneous diffraction and focusing of a nearly planar N-wave by an inhomogeneous layer in the atmosphere. This mechanism is consistent with the theory that the cause of the spikes is small scale atmospheric variations representing deviations of the atmosphere from a stratified medium.

First, a brief summary is given of the relevant experimental facts:

(1) The spikes always appear near the leading and trailing edges of what would normally be an N-wave. They are always positive.

(2) The percentage of spiked waveforms observed on a large array of microphones during a particular flight is related to the stability of the lowest portion of the atmosphere (~ 3 km).

(3) There appears to be a better than 50% probability, that, if one site receives a spiked pressure signature, an adjacent site (200 m or less away) will also receive a spiked waveform. The two waveforms may, however, be quantitatively different in the spike shape. Furthermore, the probability of highly spiked waveforms being observed at points greater than one mile apart is small.

(4) If a spiked waveform is received at a particular point during a given experiment, the repetition of the same experiment almost immediately with the same type of airplane and the same flight conditions may not produce a spiked signature at the same site.

(5) When a spiked waveform is observed, computations based on existing theories generally agree well with the signature except for the spikes.

(6) Spike heights range up to 1 psf above the normal N-wave profile, and their widths are of the order of 10 msec or less.

The mechanism developed is compatible with all of these characteristics.

The principal tenet of the theory is that small-scale atmospheric variations will cause a normally smooth acoustic wavefront to develop ripples. For relatively thin layers and weak inhomogeneities, the net rippling effect is explained on the basis of travel-time variations for different points of the wavefront. Focusing and defocusing result from the rippling of the wavefront. Focusing results from a concave ripple and defocusing results from a convex ripple.

It is shown that the net effect of diffraction is a tendency to "wash out" the magnification and demagnification effects associated with the wavefront rippling. However, the diffraction is most effective for the lower-frequency portion of the waveform. Portions of the waveform near the pressure jumps are composed primarily of higher frequencies and accordingly conform to geometrical acoustics. Thus diffraction will not be present at the wave onset, and one would accordingly expect the early portion of the waveform to be sensitive to the focusing effect. The central portion is composed of lower frequencies and is therefore less sensitive to any effects associated with focusing of rays from a limited area of the wavefront. The net effect when diffraction is present and when the ray analysis predicts a magnification is a spiked waveform. The same argument applies to the pressure jump at the trailing edge of the waveform. This mechanism, therefore, guarantees that, if a spiked waveform is predicted, positive spikes appear superimposed on each pressure jump. The time variability of the waveforms observed during consecutive experiments is attributed either to the motion of the atmospheric irregularities or to small variations in the flight paths of the two planes.

It is pointed out by the author that whether or not the mechanism discussed in this paper is the principal cause of experimentally observed spikes cannot be answered with certainty because of the lack of detailed knowledge of atmospheric inhomogeneities and of a detailed solution for transient propagation through an inhomogeneous (not stratified) atmosphere. It is noted, however, that the analysis presented here gives no indication of conflict of the theoretical results with the experimental evidence concerning spiked pressure signatures.

In an earlier paper (see capsule summary P-79) Crow developed a theory for explaining the fine structure of distorted N-waves that differs considerably from the one presented here. Crow's theory is based upon acoustic scattering theory.

P-81

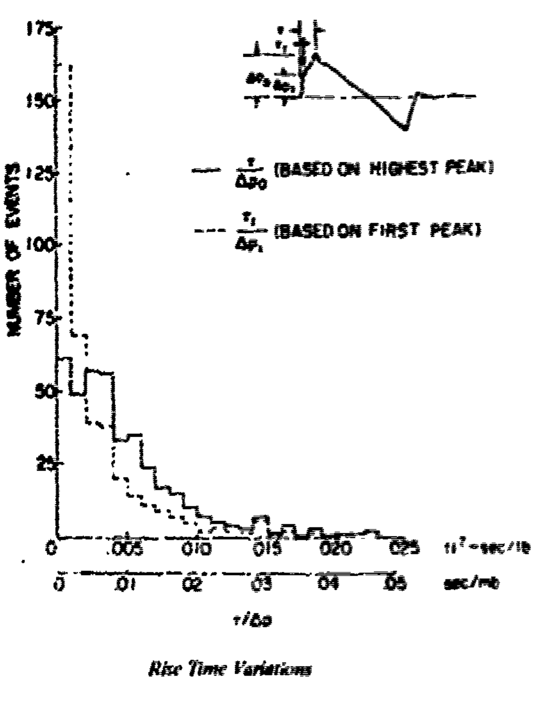
A SUMMARY OF RESULTS ON SONIC-BOOM PRESSURE-SIGNATURE VARIATIONS ASSOCIATED WITH ATMOSPHERIC CONDITIONS

I. E. Garrick and D. J. Maglieri

NASA TND-4588, May 1968

This report presents a summary of the state of knowledge concerning atmospheric effects of the sonic boom, including the results of various flight programs. Topics included are: (1) effects of atmospheric turbulence on pressure signatures; (2) atmospheric effects on energy spectra of pressure signatures; (3) lateral spread of sonic boom overpressure; (4) a statistical analysis of sonic boom overpressures and positive impulses; (5) variations in rise time; and (6) an evaluation of the effects of airplane motion. All of these topics, except the last two, are discussed in exactly the same manner in a previous paper by Garrick and Maglieri (see capsule summary P-69). The reader is referred to that capsule summary for a discussion of there topics. The last two topics are summarized below.

Variations in rise time are discussed very briefly. The figure below shows data for a B-58 airplane at an altitude of approximately 42,000 feet and a Mach number of 1.65 for measurement along the flight track. As shown in the sketch, rise time can be defined as either the time required to reach the largest overpressure (solid line) or the time required to reach the first peak. In either case, the histogram shows considerable variations in rise times.



Rise Time Variations

It is shown that aircraft motion, in the form of perturbations about the normal flight track, does not contribute significantly to observed sonic boom signature variations. This is taken as evidence that the variations discussed previously in the paper are due mainly to atmospheric effects rather than to effects of aircraft motion.

P-82
EFFECTS OF WINDS AND INHOMOGENEOUS ATMOSPHERE ON SONIC BOOM
Y. S. Pan
AIAA Journal, Vol. 6, No. 7, July 1968, pp. 1393-1395

This brief note presents the results of a study of the effects of winds and inhomogeneous atmosphere on sonic booms by use of a shock wave-vortex sheet interaction concept. The results of this investigation are presented in greater detail in an earlier paper by Pan (see capsule summary P-77). The reader is referred to that capsule summary for a discussion of these results.

P-83
ENERGY INVARIANT FOR GEOMETRIC ACOUSTICS IN A MOVING MEDIUM
Wallace D. Hayes
The Physics of Fluids, Vol. 11, No. 8, August 1968, pp. 1654-1656

An extension of the concept of conservation of acoustic energy to a flow in which the undisturbed flow is unsteady is made in this paper. The result is then applied to a ray tube.

For a motionless medium, conservation of the Rayleigh acoustic energy can be used to determine the distribution of wave intensities. Blokhintsev (see capsule summary P-3) derived an acoustic energy invariant for the case in which the undisturbed motion of the medium is steady. The present paper begins with the hydrodynamic equations and solves them in the context of geometrical acoustics (see capsule summary P-90 for a discussion of Hayes' treatment of geometrical acoustics) to show that the integral of the quantity E/Ω, where E is the classical acoustic energy density of Rayleigh and Ω is a frequency variable as measured by an observer moving with the medium, over any volume whose boundary points move with velocity $\underline{c}$ is invariant. Here $\underline{c} = a\underline{n} + \underline{u}$, where a is the speed of sound, $\underline{n}$ = unit vector normal to wavefront, and $\underline{u}$ is the wind velocity. It also noted the Ef/Ω is conserved if f is any scalar quantity for which $df/dt = 0$, where $d/dt = \partial/\partial t + \underline{c} \cdot \nabla$.

The invariant quantity is then expressed in terms of ray tube area. With A_n the area of a ray tube cut by a wave front, the quantity EaA_n/Ω^2 is constant along a ray (E = Rayleigh acoustic energy $= \rho_0 q^2/2 + p'^2/2\rho_0 a_0^2$, where ρ_0 = reference density, a_0 = reference speed of sound, q = velocity perturbation, and p' = pressure perturbation).

P-84
PROPAGATION OF THE SONIC BOOM IN THE REAL ATMOSPHERE
Antoni Tarnogrodski
ICAS Paper No. 68-32, The Sixth Congress of the International Council of the Aeronautical Sciences, Deutsches Museum, Munich, Germany; September 9-13, 1968

The theory of geometric acoustics is used to investigate the influence of vertical temperature and wind gradients on sonic boom propagation. Only rays in the vertical plane of the flight path are considered. The sonic boom intensity is not determined.

The general form of Snell's law for an atmosphere with horizontal winds is used (see capsule summary P-1) together with the differential equations for the rays and paths of the wavefronts to get parametric equations (in terms of the inclination angle of the wavefront normal to the horizontal) for the path of an element of the wavefront and for the wavefront itself.

Five different atmospheric models are then used, and the differential equations for the rays, wavefronts, and paths of the wavefront and the solutions of these equations are given both in tabular and graphical form. These five models are: (1) still, homogeneous atmosphere; (2) still atmosphere with vertical sound speed gradient; (3) still atmosphere with alternate vertical sound speed gradient; (4) homogeneous atmosphere with vertical wind velocity gradient; and (5) atmosphere with both sound and wind velocity gradients.

The theory used in this paper is not new. However, the extensive calculations made of the ray paths and wavefront expressions for various atmospheres were of potential use to subsequent investigators.

A similar but less extensive investigation of this subject is presented in a later paper by Tarnogrodski (see capsule summary P-96).

P-85
DEVELOPMENT OF SONIC BOOM PRESSURE SIGNATURES IN A STRATIFIED ATMOSPHERE
Raymond L. Barger
NASA TN-D-4890, November 1968

An extension of Whitham's theory (see capsule summary G-3) is used together with a ray-tube calculation procedure similar to that used in an earlier paper by Barger (see capsule summary P-37) to describe the development of a sonic boom pressure signature in a stratified atmosphere with horizontal winds. Throughout the analysis the atmospheric variation is assumed to be slight over a distance of the order of the length of the signature.

The basic concept used is to start with the equation for a sound ray as determined by the assumption of ordinary acoustic propagation, and then modify the equation by replacing the expression for the undisturbed sound speed by the actual speed of propagation as influenced by the finite overpressure in the wave. The following approximation procedure [illegible]

It is shown that aircraft motion, in the form of perturbations about the nominal flight track, does not contribute significantly to observed sonic boom signature variations. This is taken as evidence that the variations discussed previously in the paper are due mainly to atmospheric effects rather than to effects of aircraft motion.

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P-85
DEVELOPMENT OF SONIC BOOM PRESSURE SIGNATURES IN A STRATIFIED ATMOSPHERE
Raymond L. Barger
NASA TN-D-4893, November 1968

An extension of Whitham's theory (see capsule summary G-3) is used together with a ray-tube calculation procedure similar to that used in an earlier paper by Barger (see capsule summary P-37) to describe the development of a sonic boom pressure signature in a stratified atmosphere with horizontal winds. Throughout the analysis the atmospheric variation is assumed to be slight over a distance of the order of the length of the signature.

The basic concept used is to start with the equation for a sound ray as determined by the assumption of ordinary acoustic propagation, and then modify the equation by replacing the expression for the undisturbed sound speed by the actual speed of propagation as influenced by the finite overpressure in the wave. The following approximation procedure is used. The

ray associated with a point of zero overpressure is adopted as a "typical" ray for the signature for the purpose of determining the wavefront normal direction and the ray tube cross-sectional area. Then the nonlinear effect of the motion of the other points of the signature relative to the point associated with this ray is determined by adjusting the speed of those points to account for the finite overpressure associated with them.

First an expression is derived for the time at which the wavelet associated with the "typical" ray arrives at a level z units below the plane $z = 0$ of the airplane. In order to account for the finite overpressure associated with some other ray, the undisturbed speed of sound is replaced in this expression by the actual speed of the wavelet. The variation of overpressure along a ray tube is then determined in terms of the atmospheric properties, the ray tube area, and the F-function (see capsule summary G-3) of the airplane. These quantities are sufficient for calculating the pressure signature after the ray tube area and the direction cosines of the wavefront normal are determined as functions of altitude.

Previous theories, such as that of Friedman, Kane, and Sigalla (see capsule summary P-33) treated the wave as a single pulse and did not account for any details of the nature or development of the pressure signature. However, the present theory does account for the changes in signature shape as it propagates away from the airplane.

The method used here is very similar to that used by Hayes, et al. (see capsule summary P-98). However, Hayes, et al. incorporated their theory into a computer program which greatly simplifies the implementation of the theory.

P-86

UNIFORM RAY THEORY APPLIED TO SONIC BOOM PROBLEMS

M. B. Friedman and M. K. Myers

NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 145-149

This paper treats the propagation of shock waves from a slender body of revolution moving at supersonic speed through a stratified medium in which the ambient sound speed is a monotonically decreasing function of altitude. The purpose of this work is to develop a "uniformly valid" theory that can be applied to predicting sonic boom strength at a focus. The problem is treated using a first-order Whitham correction to the linear field. The major difficulty arising in such a procedure is the development of a uniformly valid asymptotic expansion of the linear field which is appropriate as a basis for the Whitham technique (see capsule summary G-3). Such an expansion must take into account the interaction between diffraction effects attributed to the medium and the motion of the body and the primary disturbances. It must also account for the subsequent occurrence of focusing in the field attributed to refraction of the signal by the medium.

The uniform linear field is obtained in a parametric form using a ray technique which is a generalization of geometric acoustics. The major portion of the existing theory at the time this paper was written was concerned with problems involving time-harmonic wave propagation. Thus, a major effort in the present work was to derive corresponding generalizations of geometric acoustics to describe the propagation of arbitrary pulses. The process of developing an asymptotic theory for the treatment of a general problem is shown to involve several stages employing different asymptotic expansions. The first significant stage is governed by diffraction effects. A second is associated with the formation of ray envelopes in the field as a result of these interactions.

As an illustration, the uniform expansion is used to apply the Whitham method to a two-dimensional, wedge-shaped airfoil set impulsively into uniform supersonic motion.

In an earlier paper Friedman and Myers used linear theory to investigate focusing (see capsule summary P-59). The reader is referred to the capsule summary of that paper for further details of their theory.

P-87

ATMOSPHERIC EFFECTS ON THE SONIC BOOM

I. Edward Garrick

NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 3-17

This paper presents a summary of the knowledge concerning atmospheric effects on the sonic boom as of 1968. Topics treated are: (1) effects of atmospheric turbulence on pressure signatures; (2) atmospheric effects on energy spectra of pressure signatures; (3) lateral spread of sonic boom overpressure; and (4) a statistical analysis of sonic boom overpressures and positive impulses. This paper is, basically, a condensed version of an earlier paper by Garrick and Maglieri (see capsule summary P-69). The reader is referred to that capsule summary for a discussion of the results of this paper.

P-88

MULTIPOLES, WAVEFORMS, AND ATMOSPHERIC EFFECTS

A. R. George and A. R. Seebass

NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 133-144

This paper is concerned, for the most part, with sonic boom minimization. For those results the reader is referred to capsule summary M-30. There is, however, one short section dealing with atmospheric effects on the sonic boom. This section presents results obtained by Plotkin, which were related to the authors of this paper, concerning the atmospheric correction factor. The present analysis showed agreement with the results of Randall (see capsule summary P-58) when his model atmosphere was used, and essential agreement was found with the results of Kawamura and Makino (see capsule summary P-70) for a standard atmosphere. The results differ slightly from the earlier results of Kane and Palmer (see capsule summary P-42), but these differences are only of the order of [illegible]% or less.

P-89

THE ARAP SONIC BOOM COMPUTER PROGRAM

Wallace D. Hayes and Rudolph C. Haefeli

NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 151-158

This short paper briefly outlines a computer program for the calculation of sonic boom signatures on the ground. The atmosphere is assumed to be stratified with thermodynamic properties and horizontal winds functions of altitude alone. The signal leaving the aircraft is presumed known and must be specified as input to the present program in terms of an F-function. This signal and the aircraft maneuver provide initial conditions for the wave propagation which is given by the theory of geometric acoustics (see capsule summary P-98). The calculations provide ray trajectories for the signal, and also ray tube areas to determine the strength of the signal. A modification of the signature is made with the help of an age variable to account for nonlinear distortion and the presence of shock waves. Ray tube areas are computed correctly according to geometric acoustics with both arbitrary maneuvers of the aircraft and arbitrary stratification taken into account, and actual (midfield) signatures are computed without the common simplifying assumption of an N-wave. The program simply stops when a caustic is reached, and, if a ray traveling downward becomes horizontal, no attempt is made to follow the propagation further, and the propagation computation is stopped.

The program input data and the program output information are then reviewed. Some selected results obtained with the sonic boom computer program are also given.

This computer program was published later in a NASA contractor's report (see capsule summary P-98). The reader is referred to that capsule summary for further details of this very significant work, which currently forms the basis for all correct calculations of atmospheric effects on the propagation of sonic boom signatures.

P-90

GEOMETRIC ACOUSTICS AND WAVE THEORY

Wallace D. Hayes

NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 159-164

This is a short paper which presents the theory of geometric acoustics as it emerges as a special case of the geometric theory of general linear wave propagation. It is pointed out that the study of geometric theory of wave propagation of any type starts with a study of linear solutions in a uniform medium which are proportional to functions of a phase variable $\phi = \underline{k} \cdot \underline{r} - \omega t$, with $\underline{r}$ a distance variable in a suitable euclidean space and $\underline{k}$ a vector wave number. The study yields a relation $\omega = \Omega(\underline{k})$, termed a dispersion relation. If ω is real when $\underline{k}$ is real, the waves are termed nondissipative. The solutions obtained are solutions for plane waves, the waves being planar in the $\underline{r}$ space.

In the general geometric theory for nondissipative waves, the strict conditions above are relaxed, and an asymptotic theory in a slowly varying nonuniform medium is sought for which the local solutions are very close to those obtained for plane waves, and ω and $\underline{k}$ are considered large in some relative sense. The solutions are again proportional to functions (generally sinusoidal) of a phase variable $\phi(\underline{r},t)$, and also to slowly varying amplitude functions.

An approach is outlined for the general geometric theory for nondissipative, nondispersive waves, and a study of linear inviscid theory following this approach led to the conclusion that its geometric theory is of the nondissipative, nondispersive type. The perturbation velocity $\underline{q}$ and the perturbation pressure p' are related by

$$\underline{n}p' = \rho a \underline{q}$$

where ρ = density

$\underline{n}$ = unit vector in direction of wave vector

and $\underline{a}$ = speed of sound

The dispersion relation is

$$c_n(\underline{n},r,t) = a(\underline{r},t) + \underline{n} \cdot \underline{u}(\underline{r},t)$$

where $\underline{n}/c_n$ = inverse phase velocity

and $\underline{u}$ is the undisturbed fluid velocity. The group velocity is given by

$$\underline{c} = a\underline{n} + \underline{u}$$

The quantity constant along rays is $\rho q^2 c_n{}^2 A_n/\omega^2 a$, where A_n is the ray tube area.

The case of propagation in a stratified medium is then treated briefly.

The theory discussed in this paper is equivalent to that used in the computer program developed by Hayes and Haefeli (see capsule summary P-98). However, the treatment of the present paper is less detailed than that of the earlier paper.

P-91

SIMILARITY RULES FOR NONLINEAR ACOUSTIC PROPAGATION THROUGH A CAUSTIC

Wallace D. Hayes

NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 165-171

The purpose of this paper is to examine how weak nonlinear effects are to be taken into account in the local analysis of a thin region including a caustic. A caustic in geometric acoustics is defined as an envelope of rays and also a locus of wave front cusps. A point on a caustic is one where a ray tube area is zero, but corresponds to a lowest order type singularity for points of zero ray tube area. A parameter R is used to characterize the scale size of the caustics. This scale is defined in terms of wavefront shape. Interest in this paper is with acoustic signals of characteristic length L, which may be the total length of a sonic boom signal, or the spatial period of a periodic signal.

It is stated that when the ratio L/R is sufficiently small, a boundary-layer approach is valid. Separate inner and outer solutions must be carried out

and matched. The outer analysis is one for geometric acoustics, in which weak nonlinear effects may be taken into account. The inner analysis, in a thin region including the caustic, is a local analysis with stretched coordinates. As stated above, this paper examines how weak nonlinear effects are taken into account in this local analysis.

The linearized potential equation is modified to include the caustic behavior and to take nonlinear effects into account to lowest order. The main boundary condition is one describing an incoming signal on the hyperbolic side of the caustic. In a detailed analysis, the incoming signal would be described in terms of the theory of quasi-linear geometric acoustics. In this paper the simpler course of describing the incoming signal in terms of linear geometric acoustics is taken.

The result of the derivation is a nonlinear Tricomi equation for the velocity potential together with a boundary condition which enables it to be solved. The resulting solution is a function of a basic similarity parameter K.

A linearized version of the nonlinear Tricomi equation is then studied, since in studying a nonlinear problem which reduces to a linear one in some limit, it is essential to understand the linear problem.

In an earlier paper (see capsule summary P-59) Myers and Friedman used linear theory to treat the topic of ray focusing. The present method, which takes into account the nonlinearities at a caustic, should give a better description of the flow behavior at a caustic.

P-92

SONIC BOOM GROUND PRESSURE MEASUREMENTS FOR FLIGHTS AT ALTITUDES IN EXCESS OF 70,000 FEET AND AT MACH NUMBERS UP TO 3.0

Domenic J. Maglieri

NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 19-27

This paper presents an analysis of data obtained during the Edwards Air Force Base Sonic Boom Evaluation Program conducted in the 1966-1967 time period. Sonic boom measurements were obtained from 35 flights of an SR-71 airplane at altitudes in excess of 70,000 feet and Mach numbers to 3.0. No unusual phenomena were encountered for the extreme altitude and Mach number ranges of these tests, and the results fit generally into established patterns of other available sonic boom flight data from F-104, B-58, and XB-70 aircraft. The results were as follows: (1) the overpressures were a maximum along the ground track and decrease with increasing lateral distance; (2) the prediction of the lateral cutoff point appeared to correlate well with the data for the Mach number and altitude ranges of these tests; (3) a statistical analysis showed that the variability in the positive impulse of the pressure signature is generally less than for the associated overpressures; and (4) in general, the rise time per unit overpressure increases as the altitude of the aircraft increases.

The significance of this short paper is that it demonstrated that the results concerning propagation of sonic booms for flight at lower altitudes and Mach numbers are valid also at much higher Mach numbers and altitudes.

P-93

WAVE SCATTERING DUE TO TURBULENCE

G. K. Batchelor

AIAA Sonic Boom Theory Seminar, January 1969

This is a reprint of a paper written by Batchelor in 1956. The reader is referred to capsule summary P-15 for details of this work.

P-94

VARIABILITY IN SONIC-BOOM SIGNATURES MEASURED ALONG AN 8000-FOOT LINEAR ARRAY

D. J. Maglieri, V. Huckel, H. R. Henderson, N. J. McLeod

NASA TND-5040, February 1969

The results of a flight test investigation of the variability in sonic boom pressure signatures are presented in this paper. Measurements from an 8000-foot linear microphone array indicate that wavelike overpressure patterns in which the signature shapes progress from peaked to rounded vary with time. Such variations are believed to be attributable to the atmosphere rather than to aircraft motion. Analyses of data for the same instruments, time period, airplane altitude, and aircraft type, and for Mach numbers of 1.3 and 1.6, suggest that a lesser variability in pressure, impulse, period and rise time exists for the Mach number 1.6 data.

The probability of equaling or exceeding the ratio of measured to calculated overpressure impulse, and time durations for the F-104 fighter airplane, were determined from a sample of more than 2500 data points for different operating conditions, geographical locations, and climatic conditions. The results suggest that the logarithms of these quantities follow a normal distribution.

The results found here agree with those of earlier investigations (see capsule summaries P-81 and P-65, for example).

P-95

ON THE NONLINEAR PROPAGATION OF SHOCK WAVES THROUGH NONUNIFORM INCOMING FLOWS

Sheldon Weinbaum and Arnold Goldberg

AIAA Paper No. 69-39, AIAA 7th Aerospace Sciences Meeting, New York City, New York, January 20-22, 1969

This paper presents an analysis of the propagation of an oblique shock wave through a two-dimensional steady non-uniform incoming flow. A higher order theory is developed to treat the propagation of an incident oblique shock wave through irrotational or rotational disturbances of arbitrary amplitude. The restrictions of this theory are: (1) that the flow behind the shock wave be locally supersonic as seen by an observer fixed in the reference frame of the shock wave; and (2) that the strength of the incident waves at the rear of the shock front be small compared to (a) the strength of the incoming waves of the opposite family that pass attenuated through the shock front and (b) the emitted waves of the opposite family that are produced by the vorticity or entropy interaction at the shock front.

These basic features are used to derive a new shock refraction relation for steady flows of great generality by combining the oblique shock relations with the characteristic relations at the downstream side of the shock. The coefficients of the differential equations are developed as power series in the turning angle of the flow, , about the local conditions upstream of the shock. The result is a single equation relating the differential changes in turning angle of the flow, $d\theta$, to the differential changes dp_1, $d\theta_1$, dM_1, of the flow variables on the upstream side:

$$-d\theta = \frac{1}{h + ap_1}(h \cdot d\theta_1 + b \cdot dp_1 + a \cdot c \cdot p_1 \, dM_1)$$

where a, b, c, and h are all expansions in power series of θ and Φ with coefficient functions of upstream conditions only. The downstream flow condition is represented in the equation solely by the parameter $\Phi = P_\xi/P_\eta$, where P is the pressure and (ξ,η) are coordinates based on the the characteristics. This equation prescribes the complete shock refraction problem for the general class of two-dimensional flows where the principal shock interaction occurs with the oncoming disturbed flow ahead of the shock rather than with the flow behind it and where $M_2 > 1$. Analytic and numerical solutions to this equation are presented and the results given and compared in graphical form for the following nonuniform flows: (1) a supersonic shear layer; (2) converging or diverging flow; (3) pure pressure disturbance; (4) and (5) Prandtl, Meyer expansions of the same and opposite families, (6) isentropic non-simple wave region; and (7) a constant pressure rotational flow. The comparison between analytic and numerical results was found to be very good.

Previous investigations of the effect of flow nonuniformities on the propagation of shock waves were conducted by Crow (see capsule summary P-79) and Pierce (see capsule summary P-80). These two papers were written with the purpose of explaining atmospheric distortion of sonic boom pressure signatures, while the present paper deals with shock waves in general.

P-96

PROPAGATION OF THE SONIC BOOM IN THE STILL ATMOSPHERE WITH TEMPERATURE GRADIENT

A. Tarnogrodzki

Archiwum Mechaniki Stosowanej, March 1969, pp. 271-279

In this paper a still atmosphere with constant vertical temperature gradient is considered, and a graphical method of determination of rays for arbitrary motion of an aircraft and a simple numerical method for determining the wavefront are presented.

Parametric equations for the vertical and horizontal coordinates of the rays are derived from Snell's law (see capsule summary P-1) in terms of the azimuthal angle and Snell's law constant. Four characteristic cases of flight are then considered: (1) $\Gamma = 0$; (2) $\Gamma = \alpha$; (3) $\Gamma = \pi/2 - \alpha$; and (4) $\Gamma = \pi/2$, where Γ = angle of climb and α = Mach angle. For each of these cases, a tabulation of the value of the constant in Snell's law is made for each of the Mach number ranges $\alpha < \pi/4$ and $\alpha > \pi/4$. Knowing this constant and the parametric equations of the ray allows a graphical determination of the ray.

Parametric equations for the wavefront at a particular instant are derived in terms of the azimuthal angle θ and τ, which is the time at which the nose of the airplane passed through the starting point of a particular ray. Using a relation derived between time and inclination angle ϕ and the parametric equations of a ray, the coordinates of the element of the wavefront in the vertical plane beneath the airplane at a given time can be determined.

A similar but more detailed investigation was presented in an earlier paper by Tarnogrodski (see capsule summary P-84).

The case of a still atmosphere with a linear vertical temperature gradient was treated much earlier by Randall (see capsule summary P-11). The present paper merely repeats this derivation, and the graphical and numerical methods developed here are of limited use.

P-97

EFFECTS OF ATMOSPHERE, WIND, AND AIRCRAFT MANEUVERS ON SONIC BOOM SIGNATURES

R. C. Haefeli

NASA Contractor Report, NASA CR-66756, April 1969

The computer program developed by Hayes, Haefeli, and Kulsrud (see capsule summary P-98) for computing sonic boom propagation in a stratified atmosphere with winds is used in this paper to obtain results for a wide variety of aircraft maneuvers and atmospheres. These results cover a broad scope of variation of parameters to point out significant effects and parameter sensitivities, and to provide a general source of data for sonic boom evaluations. Both a fighter type aircraft (F-104) and an SST-type (SCAT-15F) were used as a basis for these calculations. Complete F-functions were used as input for determining their overall pressure signatures as distorted by nonlinear propagation effects. These signatures included all of their shock waves.

Parametric data are presented which show the sonic boom overpressure, the length of the signature, the ray-travel time and the ray-ground distance for various atmospheres, winds, aircraft Mach numbers and altitudes. Features of the digital program are demonstrated showing where ray-ground intersections and shock-ground intersections occur for turn maneuvers, along with other geometric and sonic boom characteristics.

Comparisons of overpressures with previous analytic results are made. These are restricted basically to uniform flight inasmuch as previous analyses did not include capabilities for calculating overpressures for general aircraft maneuvers. They do, however, include variations of atmospheric temperature profile, wind speed and direction, and aircraft Mach number. The agreement with the results of Kane and Palmer (see capsule summary P-42) for those uniform flight conditions which were examined is excellent, although differences were found for some conditions near ray focusing.

Several comparisons of overpressures with previous experimental results for accelerating and porpoising

flight are also made. For the accelerating flight, good agreement with measured overpressure was found, except a displacement of about 2 miles in the ground location which cannot be explained. For the porpoising flight, significant effects of the flight path angle rate on the signature shape and overpressure were calculated, although no such effect was found in the flight measurements.

The results concerning the pressure signature variations with both atmospheric and flight conditions are summarized as follows:

(1) For the airplanes considered the variation of the signatures with aircraft altitude and propagation distance shows that a large part of the aging of the signal occurs within the first few thousand feet of propagation distance. The pressure signature represented by the initial F-function distorts very rapidly and, for complex F-functions, multiple shock waves quickly appear. Some of these shocks merge as the wave front continues to travel through the atmosphere, but the signature at the ground need not be a fully developed N-wave. In general, aging in a standard atmosphere exhibits an asymptotic limit whereas in a uniform atmosphere aging increases indefinitely.

(2) Overpressure ratios are not independent of aircraft type, so that detailed evaluation of sonic boom characteristics may require data to be generated for each specified aircraft. Also, realistic atmospheres (such as the 1962 U.S. standard) and complete signatures should be used for specific sonic boom analysis.

(3) The lengths of the signatures calculated with realistic atmospheres are shorter than the lengths calculated with uniform atmospheres.

(4) Effects of wind-speed profile and wind direction were also analyzed. It was shown that highest overpressures occur with the headwind for ray paths both on and off the flight track.

(5) Large overpressures may result from longitudinal acceleration, pushover, and turn maneuvers.

This paper does an excellent job of demonstrating the utility and validity of the Hayes-Haefeli-Kulsrud computer program. It also demonstrates the accuracy of the simpler methods of Kane and Palmer in predicting sonic boom propagation for uniform flight conditions of current supersonic airplanes.

[illegible]-98
SONIC BOOM PROPAGATION IN A STRATIFIED ATMOSPHERE, WITH COMPUTER PROGRAM
W. D. Hayes, R. C. Haefeli, H. E. Kulsrud
NASA Contractor Report, NASA CR-1295, April 1969

Sonic boom propagation in a horizontally stratified atmosphere with winds is analyzed in this report. The analysis is, to some extent, a synthesis of established theory but with many new features. Also, a computer program based on the analysis is given.

The report is divided into two main parts--one giving an exposition of the basic theory and development of the equations, the other describing and listing the computer program and presenting sample results. The first part begins with a general description of the theory, with accent on the physical reasoning and motivation underlying the analysis. In the course of the analysis, brief statements are included on its application in the computer program. In addition to current references, there are some historical notes appended.

The second part, consisting of the computer program and the computation results, includes a complete description of the program, with tables giving the FORTRAN nomenclature used for various variables and subroutines, and with a program listing. Sample input and output listings are included, and typical computation results are presented.

The analysis consists of three main parts. The first part concerns the calculation of the rays and ray tube areas for zero phase (the reference phase). The second part concerns the calculation by linear theory of acoustic signals along each geometric ray. The third part concerns the calculation, with shocks properly accounted for, of the nonlinear distortion of the signal.

A critical assumption is that of steady ray geometry. This means that the rays corresponding to values of the phase other than zero follow the same paths as do the rays for which the phase is zero. Phase is defined here as the time measured from the passage of the reference (zero phase) wavefront. The justification given for this assumption is the thinness of the entire wave system of interest. This is a result of the fact that the aircraft length is small compared with other macroscopic characteristic scales. A ray emanating from the tail is simply so close to the corresponding one of zero phase that the difference in their ray paths may be neglected. Thus this assumption is sound even though the problem with a maneuvering aircraft is not a steady one. This permits the aircraft to be considered as a single moving point in space.

The maneuver of the aircraft, which is represented by a reference point, is required in detail. Variables are introduced in the section on aircraft maneuvers which describe the trajectory in space, the orientation of the flight axis, the velocity of the aircraft relative to the local atmosphere, and the local sound speed, all as functions of time along the aircraft trajectory t_a. Time derivatives of some of these variables are also determined, for later use in the ray-tube area calculation. A Mach cone attached to the nose of the aircraft is visualized at each instant t_a. The normals to the Mach cone form a one-parameter family of directions forming a wave-normal cone with the parameter being an azimuth angle ϕ. The two quantities t_a and ϕ are the parameters used to characterize the rays.

In the section on Mach conoids and ground intersections, the wave fronts and rays from an aircraft in maneuvering flight are discussed generally, with particular attention to the intersections of the rays and wave fronts with the ground.

The generators of the wave-normal cone at the aircraft are the initial wave normals for the calculation of the rays. The orientation of these

normals is known as a function of the ray parameters. For each wave normal two quantities are calculated which are invariant on rays according to the appropriate Snell's law. These invariants are then used to calculate the ray trajectories.

The ray tube area is defined as that given by horizontal cutting planes. An analytic expression for this area is obtained in terms of the maneuver variables, certain of their time derivatives, and three quadratures along the ray. The ray tube area is thus obtained as a function of altitude along each ray and may be calculated concurrently with the ray trajectory.

For the second part of the analysis, the flow close to the aircraft is considered first. In particular, the asymptotic form of the local solution is computed, valid at a distance from the flight axis large compared with the effective lateral dimensions of the aircraft but small compared with characteristic scales for the atmosphere. This asymptotic form of the local solution is interpretable as a geometric acoustics solution. At a sufficiently large distance r in a particular direction away from the flight axis of the aircraft, the solution appears the same as that from an equivalent body of revolution (see capsule summary G-1). The pressure perturbation in the asymptotic solution is proportional to $r^{-1/2}$ times a function F, related to Whitham's F-function (see capsule summary G-3), of a suitably defined phase and an azimuth angle ϕ_r (simply related to ϕ). This F-function depends also upon the Mach number and lift coefficient of the aircraft, which are functions of the time t_a. The F-function is then a function of phase and of the ray parameters t_a and ϕ and is invariant along each ray. It is obtainable either by a computation or from experiment. It is assumed to be a known function in the computer program.

In the general stratified atmosphere with winds, the phase ζ is defined to be the time measured by an observer fixed in a ground-based coordinate system and defined to be zero the instant the zero-phase wave front passes. Invariance results of Blokhintsev (see capsule summary P-3) are used to describe the acoustic signal in terms of a function $V_e(\zeta)$ which is constant on the ray.

The function F is then expressed as a function of ζ, and the relation between F and V_e is also found, which then gives the function $V_e(\zeta)$ for each ray (since F is assumed known). The relation between V_e and pressure perturbation P is known, so that $\Delta P(\zeta)$ is determined at any point on each geometric ray.

In the third part of the analysis, the change in propagation speed proportional to the strength of the signal is considered. This nonlinear effect does not, in principle, influence the magnitude of the pressure perturbation in the acoustic signal. Rather, it causes phase shifts in the signal, whereby a given point in the signature may appear earlier or later than predicted by the linear theory. In terms of the phase variable ζ, this phase shift equals V_e times an "age variable" τ which can be computed along each ray by a quadrature. The distorted signal appears as the original one $V_e(\zeta)$ sheared by an amount proportional to τ

The distorted signal may be multivalued and may thus give several values of the pressure perturbation for a single value of ζ. A separate analysis shows where shock waves must lie and shows which parts of the signal have been "eaten up" by the shocks and no longer appear. The result of the analysis is the complete, single-valued pressure signature at any desired point, with shocks shown if they are present.

The theory fails near a caustic, which is a surface in space at which the ray-tube area becomes zero. It also fails near the boundary of a shadow zone into which no rays penetrate and may fail near a critical ray for which the F-function is singular in some way.

Friedman, Kane, and Sigalla (see capsule summary P-33) had previously developed a computer program for calculating the propagation of sonic booms in a stratified atmosphere with winds. Their method was also based upon the theory of geometric acoustics. However, their method assumed an N-wave pressure signature existed over the entire path of propagation, whereas the present method accounts for the variation of signature shape as the wave propagates away from the airplane and allows midfield signatures to be computed at any altitude. This is a very significant improvement.

This is one of the most important papers written on the subject of sonic boom propagation. At the present time this paper exemplifies the state of the art of sonic boom theory.

P-99

PROPAGATION OF AN N WAVE ACROSS A NONUNIFORM MEDIUM
Y. S. Pan
AIAA Journal, Vol. 7, No. 4, April 1969, pp. 788-790

This short note presents an analysis of propagation of an N-wave across a nonuniform medium described by a cloud layer or a front layer based upon the methods of geometrical acoustics (see capsule summary P-8). It is found that substantial variations of strength of the front shock and of wave shape could be produced by the assumed small variations of refractive index. The vicinity of caustics or focal points is avoided since the geometric acoustics approximation is not valid in those regions.

The effect of a horizontally stratified atmosphere on sonic booms was considered in a previous paper by Pan (see capsule summary P-77). However, the significance of the present paper is that the upper edge of the cloud layer is assumed to be curved, which means that parallel rays entering the layer at different points will be refracted differently, in contrast to the stratified atmosphere model of the earlier paper.

This was the first attempt to explain the effect of cloud layers and fronts on sonic boom propagation. However, the results have yet to be verified experimentally.

P-100

A PRELIMINARY STUDY OF THE ATMOSPHERIC EFFECTS ON THE SONIC BOOM
K. Angell, G. A. Herbert, W. A. Hass
AGARD Conference Proceedings No. 42, May 1969, pp. 26-1 through 26-11

This paper is exactly the same as a later paper which appeared in the Journal of Applied Meteorology (see capsule summary P-103). The reader is referred to that capsule summary for details of this work.

P-101
GROUND CONFIGURATION EFFECTS ON SONIC BOOM
D. Dini and M. Nuti
AGARD Conference Proceedings No. 42, May 1969, pp. 25-1 through 25-29

The effects of reflection and diffraction resulting from various ground-building configurations on the intensity of sonic booms are analyzed in this paper. Many other aspects of the sonic boom problem are also discussed.

It is shown that, from a general point of view, the ground configuration regarding large areas has no predominant effect on the sonic boom. Some sort of multiple echoes on rough ground, building populated areas, concentration of different slope and orientation surfaces, mountain peaks and cavities may amplify considerably the sonic boom effects on people and structures. But, essentially, the ground configuration effects in their dangerous actions are concentrated in small regions, where energy from incident and reflected waves is combined. In these small regions the local overpressures may reach unpredicted values much more than twice the incident ones. A very sketchy discussion of experimental data showed that on certain occasions the overpressure was quadrupled or more. Twice the normal overpressure was recorded fairly often. (The circumstances under which these measurements were obtained are not discussed.)

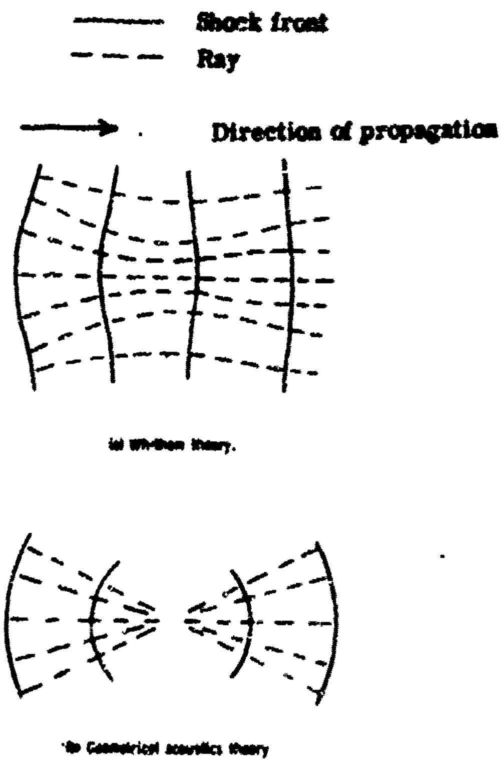
Brooks, Beasley and Barger (see capsule summary P-112) used a spark-generated N-wave to test the effects of reflection and diffraction by buildings on the intensity of sonic booms. Their results showed, among other things, that there is a region of increased overpressure near the forward base of the building, which agrees with the findings of this paper. Brooks, et al., treat the subject of building reflection and diffraction effects in much more depth than that of the present paper, however.

P-102
A LABORATORY INVESTIGATION OF N-WAVE FOCUSING
W. D. Beasley, J. D. Brooks, and R. L. Rogers
NASA Technical Note, NASA TN-D-5306, July 1969

The results of a laboratory investigation of the focusing of an N-wave at a point and along a line are presented in this paper. The N-wave was created by a spark at the focus of a parabolic mirror which reflected the N-wave as a plane wave and directed it toward the focusing mirror. Microphone traces of the signature were obtained for various positions of the wave relative to the focus, and schlieren photographs of the passage of the N-wave through the line focus were obtained.

The results indicated that shock-wave behavior in the vicinity of a point or a line focus followed the laws of geometrical acoustics. When a spark-produced wave, having an amplitude of the order of that produced on the ground by a supersonic flight (about 2 psf), was reflected from a two-dimensional parabolic mirror, a line focus was produced. When the wave passed through the focus, it underwent a componentwise shift in phase of $\pi/2$ radians. The corresponding experiment performed with a three-dimensional mirror gave a phase shift of π radians resulting in a complete inversion of the wave. Although the data indicated the occurrence of significant amplification in the vicinity of a focus, the very large amplitudes predicted by ray-tube theory were not obtained. These amplitudes were influenced by such factors as the wavelength, microphone response, mirror astigmatism, and mirror dimensions. Consequently, the authors felt that it was doubtful that any conclusions concerning the variation of amplitude in the neighborhood of the focus of a wave resulting from a supersonic flight could be drawn from these results.

The main significance of this paper lies in the finding that the phase shift of a wave when it passes through a focus is the same as that predicted by geometric acoustics. Whitham (see capsule summary P-17) had earlier derived a theory which predicted that the inherent stability of plane waves would preclude focusing, which is, of course, contradictory to the results of this paper. Friedman (see capsule summary P-27) had also predicted that complete focusing of a wave would not occur. The figure below, which was taken from this paper, shows the essential difference between the theories of Whitham and Friedman on the one hand and geometric acoustics on the other.



Conflicting Theories

Later numerical work by Parker and Zalosh (see capsule summary P-161) indicated that the Whitham-Friedman process was correct in the case of strong shocks and the geometric acoustics process was correct for weak shocks. Since a shock with an overpressure of 2 psf can hardly be considered to be strong, the results of the present experiment are in agreement with the findings of Parker and Zalosh.

This paper is significant in that this was the first attempt to experimentally determine whether or not complete wave focusing actually occurs.

P-103
A PRELIMINARY STUDY OF ATMOSPHERIC EFFECTS ON THE SONIC BOOM
G. A. Herbert, W. A. Hass and J. K. Angell
Journal of Applied Meteorology, Vol. 8, Aug. 1969, pp. 618-626

Atmospheric effects on sonic booms are investigated in this paper by analyzing more than 4000 pressure signatures generated by F-104, B-58, and XB-70 aircraft during the fall and winter of 1966-67 at Edwards Air Force Base. The airplanes flew steady, level flights at various Mach numbers over a microphone array.

The computer program of Friedman (see capsule summary P-47) is tested against the mean observed overpressure on the array and is found to be in error by an average of 10% when the maximum observed overpressure is derived from the positive impulse area. The pressure signatures are grouped into three categories, so that "spiked" signatures, which constitute the largest deviation from the mean, may be studied as a function of local weather conditions. Good correlation is found between the depth of the surface mixed layer and the percentage of spiked signatures. Under essentially surface-inversion conditions there were no spiked traces and 92% of the traces were rounded. However, when there was a deep mixed layer, 23% of the traces were spiked and only 41% were rounded. The variability of the maximum overpressure was also found to increase with an increase in low-level wind speed. It is concluded, as a result of these findings, that turbulence in the planetary boundary layer is the main cause of spiked signatures and the associated large variation in maximum overpressure. Some evidence was also found that waves within an inversion contribute to overpressure variability on a larger scale.

A later paper by Herbert (see capsule summary P-110) also deals with the material presented here. The reader is referred to the capsule summary of that paper for further details of this work.

P-104
SOME ASPECTS OF THE THEORY OF SONIC BOOM PROPAGATION THROUGH THE ATMOSPHERE
G. T. Haglund
Boeing Document D6-[illegible]607 TN, Sept. 29, 1969

A detailed analysis of six different ray-tube area equations is presented in this document. The equations analyzed are those of Barger (see capsule summary P-85), Boeing (see capsule summary P-33), Friedman (see capsule summary P-47), Hayes (see capsule summary P-33), Lilley (see capsule summary P-57), and Randall (see capsule summary P-[illegible]). The nomenclature of the equations is standardized, and it is shown that the Hayes and Barger equations are equivalent to Randall's ray-tube area equation, and, after a correction to Friedman's equation is made, it is shown to be equivalent to the Boeing equation.

The Boeing equation is the simplest, involving a one-dimensional area, while Randall's is two-dimensional. Lilley's ray-tube area equation takes into account the curvature of the shock front, but may need to be corrected.

The effect of the Boeing, Randall, and Lilley ray-tube area equations on sonic boom overpressures was considered. It was found that the Boeing ray-tube area equation results in only about 2 percent greater overpressures than Randall's in a standard atmosphere with no wind. Lilley's equation, however, gives a 14 percent greater overpressure than Randall's at Mach 1.2.

A comparison of the Boeing and Friedman computer models with actual data showed that the Boeing model is, in general, more accurate than the Friedman model. The average absolute deviation of the Boeing model predicted overpressures from the observed overpressures were about 0.2 psf or about 20 percent average error. However, large deviations were common and were attributed to small-scale atmospheric effects, for which the models do not account. It is concluded that the Boeing model accounts for the large-scale atmospheric effects correctly, on the average, while the Friedman model has errors in its ray-tube area and overpressure equations, and the aircraft volume and lift effects need improving. The Randall-Hayes expression is even more complete than the Boeing expression, however, and is now the one that is in general use.

This is an excellent paper, correlating as it does the myriad of expressions that have been derived for the ray-tube area.

P-105
EFFECTS OF AN ISOBARIC, INHOMOGENEOUS ATMOSPHERE ON SONIC BOOM
W. F. Merzkirch
Journal of Aircraft, Vol. 6, No. 5, Sept.-Oct. 1969, pp. 477-478

The purpose of this paper was to obtain incremental effects on asymptotic pressure waves due to temperature gradients and winds by assuming that these can be separated from those due to atmospheric pressure. This was accomplished by considering the special case of a stratified atmosphere having no vertical pressure gradient. This resulted in an important simplification of the governing equations. Since the real atmosphere is far from being isobaric, only the surface layer near the ground was considered, the vertical extension of which is much smaller than the normal flight altitudes of supersonic aircraft. This layer is dominated by influences of weather and exhibits noticeable changes in temperature and wind.

The problem was described by a simple, analytic equation that relates the intensity of the compression wave to the local Mach number M of the freestream. This equation is:

$$(\Delta P/\Delta P_o) = (M/M_o)\left[(M_o^2 - 1)/(M^2 - 1)\right]^{1/4}$$

where ΔP = pressure change across the wave

M = Mach number

M_o, P_o are initial values

Using this equation, the strength of the sonic boom on the ground can be determined as follows: (1) The strength of the sonic boom on the ground is calculated using one of the well-known methods for a standard atmosphere (see capsule summary P-33, for example). This corresponds to a set of initial values M_o, ΔP_o; (2) Then the deviations from the standard atmosphere in the weather layer due to wind and to temperature changes are converted to changes in Mach number. ΔM may be either negative or positive, depending on the directions of the temperature gradient and wind; (3) having the new Mach number $M = M_o + \Delta M$, the corresponding pressure change ΔP of the sonic boom can be determined from the above equation.

Pan presented a similar simplified method of determining the effect of winds and inhomogeneous atmosphere on sonic booms (see capsule summary P-77). However, Pan's method requires the numerical evaluation of a series of n products, while the present technique does not.

P-106

SONIC BOOM WAVEFORMS AND AMPLITUDES IN A REAL ATMOSPHERE

A. R. George, K. J. Plotkin

AIAA Journal, Vol. 7, No. 10, Oct. 1969, pp. 1978-1981

A simple method for determining sonic boom waveshapes and amplitudes in a still stratified atmosphere is presented in this paper. The effects of acoustic impedance, ray tube area, and nonlinear wave steepening and shock formation are each treated separately. Only the steady flight case is considered, making it possible to present all the information necessary to find sonic boom waveforms and amplitudes directly below the flight track without the use of a computer.

First, it is shown that the amplitude of an initial pressure wave form is scaled by factors C_I and C_A accounting for acoustic impedance and ray tube area changes during the wave's propagation in the atmosphere. This gives

$$P = C_I C_A \delta P_h$$

where δP = perturbation pressure of wave relative to local P

h = reference altitude where initial P curve is given

C_I and C_A are determined using the ray tube energy invariant (see capsule summary P-3, for example) and an expression for the ray tube area derived using Snell's law (see capsule summary P-1).

C_I and C_A are given by

$$C_I = (\rho a/\rho_h a_h)^{1/2}, \quad C_A = (A/A_h)^{-1/2}$$

where ρ = density

a = speed of sound

A = ray tube area

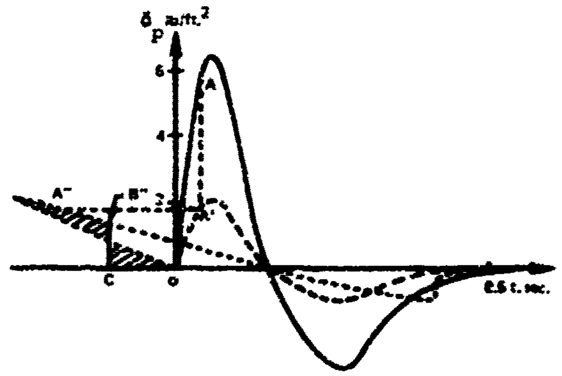
Next the nonlinear effects on the wave propagation are accounted for. It is shown that the cumulative nonlinear effects on the wave shape are accounted for by adjusting the time of arrival of each part of the wave by

$$\Delta t = C_T(\delta P/P)_h \, r_h^{1/2}$$

where r = radius from flight path

An expression is derived for C_T in terms of the atmospheric properties, ray tube area, and Mach number. Finally, shock waves are inserted using the method of Whitham (see capsule summary G-3) making the P curve single-valued.

The figure below, which was taken from this paper, illustrates the use of this method. An idealization of a curve obtained by standard area rule methods (see capsule summaries G-3 and G-6) for r_h = 500 feet and r = 60,000 feet is shown as the solid line in the figure. C_I and C_A are determined either from their equations or from figures given in the paper. For M = 3.0, multiplication by $C_I C_A$ moves a typical point from A to A' resulting in the dashed curve. Next each point on the curve is advanced in time by $C_T\ (\delta P/P)_h r_h^{1/2}$ resulting in the dotted curve by moving points from A' to A", for example. Finally, shocks are inserted in the appropriate places.



Example of Application

In a later paper (see capsule summary P-119) Haglund and Kane derive intensity and "age" scaling factors analogous to those presented here. The method used is slightly different from that of the present paper, however. Haglund and Kane scale the F-function itself (see capsule summary G-3), while the method of the present paper scales a δP wave at a reference altitude, r_h, below the airplane. When this difference is taken into account, the two methods give the same results.

This is a very well-written paper, and the method presented is very useful for situations where quick hand calculations of sonic boom intensities are desired.

P-107
SONIC BOOM PROPAGATION FROM MANEUVERING AIRCRAFT
R. C. Haefeli
AIAA Paper No. 69-1134, AIAA 6th Annual Meeting and Technical Display, Oct. 20-24, 1969

The investigation presented in this paper uses the computer program developed by Hayes, Haefeli, and Kulsrud (see capsule summary P-90) to calculate sonic boom pressures for both uniform and maneuvering flight conditions. A brief discussion of the theory is given, including the effects of acceleration on the ray-tube area. Sonic boom overpressures and complete signatures are then presented for uniform flight, pullups, pushovers, and circular turns. Results are given for both a fighter-type and SST-type aircraft. The main findings are: (1) the sonic boom signature changes rapidly in the vicinity of the aircraft; (2) the overpressures at the ground may be affected significantly by aircraft acceleration; and (3) the changes in overpressures caused by maneuvers of the SST-type aircraft are not proportional to those of the fighter for some flight conditions.

This paper is, basically, a condensation of an earlier paper by Haefeli (see capsule summary P-97). The reader is referred to that capsule summary for a more detailed discussion of this work.

P-108
THE ATMOSPHERIC CORRECTION FACTOR FOR SONIC BOOM PRESSURE AMPLITUDES
Allan D. Pierce and Charles L. Thomas
Journal of the Acoustical Society of America, Vol. 46, No. 5 (Part 2), 1969, pp. 1366-1380

The principal result of this paper is an expression for the atmospheric correction factor K_A, which represents the ratio of sonic boom overpressure at a given point due to an aircraft moving at constant supersonic speed in a temperature and wind stratified atmosphere to that which would be expected if the atmosphere were homogeneous. The derived K_A is independent of aircraft parameters and depends only on flight Mach number, altitude of flight, and the atmospheric profiles. The manner of derivation gives K_A as a product of two factors: one derived from linear geometrical acoustics using the eikonal approximation as given by Blokhintzev (see capsule summary P-3), and the other representing nonlinear effects whose derivation is based on the premise that an N-wave is developed within 10,000 feet of the flight path which propagates along the ray paths derived from geometrical acoustics. Computations of K_A illustrating the effects of atmospheric inhomogeneity show qualitative agreement with computations of Hayes, Haefeli, and Kulsrud (see capsule summary P-90), and show substantial quantitative agreement, although with some discrepancies, with previous computations by Kane and Palmer (see capsule summary P-42). A critique of the theory on which the latter computations were based is given, and it is suggested that the cause of the discrepancies could be an inadequate approximation for ray-tube area. This finding is in agreement with that of an earlier paper by Friedberg (see capsule summary P-68).

The chief advantage of the K_A derived in the present paper is its relative simplicity. According to the authors, a desired value is easily computed by hand with a relatively short expenditure of time. Furthermore, the expression is readily amenable to further simplifying approximations. It must be remembered, however, that this expression is valid only in the far field, where the signature development is not affected by the configuration shape.

P-109
REFLECTION AND FOCUSING OF SONIC BOOMS BY TWO-DIMENSIONAL CURVED SURFACES
Jack Werner
New York University, School of Engineering and Science, Report No. NYU-AA-69-35, April 1970

Starting with the acoustic wave equation, an integral relation is derived in this paper which describes the pressure due to a plane wave of arbitrary wave form incident on a two-dimensional curved surface with plane asymptotes. Pressure is given in terms of integrals involving the pressure distribution over the surface. In principle this relationship represents an integral equation for the pressure on the wall. Its form is such that this integral equation may be solved by numerical techniques. The integral relation would then become a direct expression for the pressure at any point in time and space. A criterion for the locus of focal points was developed and used to obtain an expression for the locus of such singularities. The pressure disturbance in the neighborhood of these focal points was investigated for incident step function, linear, and N-wave forms. It was found that in the case of the N-wave the major contribution to the disturbance near the focal points comes from the reflection of the discontinuities at the leading and trailing edges of the incident wave.

In a later investigation (see capsule summary P-127) Peschke studied the time history of the surface pressure due to sonic boom interaction with several topographic configurations, including rectangular buildings, spheres, and a parabolic canyon model. However, no curved two-dimensional surfaces were used. Thus the results of the present paper still await experimental verification.

P-110
SONIC BOOM METAMORPHOSIS
G. A. Herbert
Paper presented at Fourth Conference on Aerospace Meteorology, May 4-7, 1970

An investigation into the cause and frequency of spiked and rounded sonic boom pressure signatures is presented in this paper. The data reported in this study were generated, for the most part, by supersonic bomber aircraft (B-58) during the June 1966 phase of the Edwards Air Force Base sonic boom experiments. In all cases considered, the aircraft was in level, unaccelerated flight at altitudes in excess of 9 km and at speeds ranging from Mach 1.4 to 1.8.

The results of the investigation show that the intensity and shape of sonic boom signatures

recorded at ground level are strongly dependent upon the boundary layer stability of the atmosphere. The table below, which was taken from this paper, shows the signature shape distributions and average rise times for different atmospheric conditions. It shows that, while rounded waves are most common in all stability classes, they completely dominate the shape population in surface-inversion conditions. A shift in the population from rounded to nominal and spiked shapes occurs when a mixed boundary layer is present.

SOUNDING TYPE	DATA COUNT	ROUNDED %	ROUNDED t(ms)	NOMINAL %	NOMINAL t(ms)	SPIKED %	SPIKED t(ms)
SURFACE INVERSION (A)	234	84	12	6	3	2	–
SHALLOW MIXED LAYER (B)	[illegible]	51	11	35	5	14	4
DEEP MIXED LAYER (C)	380	41	11	39	5	20	4
UNSTEADY CONDITIONS (D)	310	63	15	21	[illegible]	16	4

Signature Shape Distributions and Average Rise Times for Different Atmospheric Conditions

With an increase in wind speed and the growth of a turbulent boundary layer a corresponding increase was observed in pressure fluctuations on individual signatures from one to the next. Furthermore, when boundary conditions were steady in time there were fairly small changes in the variation statistics from one boom occurrence to the next. An absence of relatively large scale (1 km) influence was found. In the case of transitional (unsteady) boundary conditions there was considerably more input to the variability by long wave components. Also, for this case a large distribution change was found to occur from one boom realization to the next. In comparable flight conditions, 7 km off-track flights yielded relatively larger amplitude variation than overhead flights. It is concluded that this latter result, along with the observed variability increase with increasing mixing depths, indicates the effect of the transit distance through the mixed layer on the variability.

The present paper deals very little with theory. However, it does an excellent job of demonstrating the types of atmospheric conditions which are conducive to the various types of distortion.

P-111
PREDICTION OF GEOMETRY OF SONIC BOOM WAVES INCIDENT ON ARBITRARILY ORIENTED PLANE WALLS
B. M. Rao, G. W. Zumwalt
J. Aircraft, Vol. 7, No. 3, May-June 1970, pp. 256-260

In this paper two analytical methods are developed for computing the arrival time of incident and ground-reflected waves of a sonic boom acting on any given exterior wall which is exposed to the unobstructed shock wave. Method I assumed a linearly-varying speed of sound up to the tropopause and constant speed of sound above the tropopause. This method was based on a ballistic wave analysis similar to that used by Lansing (see capsule summary P-43). In this approach the main point of interest is the wave fronts rather than the rays. The expression for the wave fronts together with the expression describing the envelope of these wave fronts and the geometric relations between the wave and wall for a given flight altitude, direction, and Mach number are used to derive an expression for the elapsed time between the passage of the aircraft over a point of origin O on the ground and the arrival time of the shock wave at a point P on the building. An expression is also derived for the time interval between the arrival of incident and reflected waves at point P. The above procedure is valid only for flight altitudes below the tropopause. For flight altitudes above the tropopause a more complex iterative method is developed for computing local arrival times of the incident and reflected sonic boom waves.

Method II modified method I with a simplifying assumption that the ray angles in the lateral direction from the flight path were constant. This resulted in explicit relations for the arrival times of the incident and reflected shock waves even for altitudes above the tropopause.

A comparison of the two methods showed that method II, in spite of its simplified assumption of constant ray angles, gave results which were in very good agreement with the results of method I. It is concluded that, in the absence of better meteorological information, either of the methods are very effective tools to predict the arrival times of incident and reflected waves on arbitrarily oriented plane walls. However, method II, with its simplified assumption of constant ray angles in the lateral direction, is very simple for computation and is recommended by the authors.

Flight Mach number	Flight altitude, ft	Lateral distance, ft	T, sec: Method II	T, sec: Flight testing	T_r, sec: Method II	T_r, sec: Flight testing
[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	41	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

Comparison of Theoretical Arrival Times of Sonic Boom Waves With Flight Test Data

Knowing the time of arrival of the wave at several points of a wall allows the geometric relationship between the wave and the wall to be found. This allows the structural response of the wall to be predicted if the strength of the sonic boom is known.

P-112
LABORATORY INVESTIGATION OF DIFFRACTION AND REFLECTION OF SONIC BOOMS BY BUILDINGS
J. D. Brooks, W. D. Beasley, R. L. Barger
NASA Technical Note, NASA TN D-5830, June 1970

A method for the laboratory simulation of the diffraction and reflection phenomena that occur from an N-wave passing over a building is presented in this paper. The method utilizes a

plane N-wave obtained from the reflection of a spherical N-wave generated by a spark at the focus of a parabolic mirror. Building models of various shapes and sizes were exposed to these N-waves.

The variation of overpressure obtained by varying microphone location, building dimensions, and shock angle yielded significant information on the reflection and diffraction phenomena that occur when a shock wave passes over a building. The area in the shadow zone behind the building is not entirely shielded from the boom but is subjected to the waves diffracted into this region. Although the shielding effect generally tends to increase with building dimensions, the actual pressure at any point in the shadow zone depends on the phase of the wave diffracted over the top relative to the phase of the waves diffracted around the ends of the building.

The overpressures within a certain region of the direct wave adjacent to the shadow zone are reduced as a result of the loss of energy by diffraction into the shadow zone. This type of mechanism also, in effect, reduces the reflection coefficient on the forward face of a building for some distance down from the top edge, so that for a relatively low building the overpressure over the entire forward face is somewhat reduced.

Although the averaging effect resulting from using a microphone that was large relative to the wavelength prevented an accurate measurement of the peak overpressure at the forward face of the building, significant intensification of the overpressure in this region was measured. However, the results indicate that except possibly for exceptionally large buildings, diffraction phenomena would prevent this overpressure from reaching the level of four times the incident pressure that would be expected for large buildings.

Measurements obtained for L-shaped buildings and cylindrical buildings indicate that significant reduction in the forward face pressure can be obtained by appropriate architectural design.

Sauer and Bagley (see paper summary P-113), conducted a similar investigation concerning the effect of building reflections on sonic boom overpressures. The boom wave overpressure measurements in that paper were much more accurate than those of the present paper, and it was found that the overpressures at the forward face of a building are approximately four times the incident pressure, in contrast to the expectations of the authors of the present paper. Diffraction effects were not investigated by Sauer and Bagley.

In spite of the inaccurate overpressure measurements, this is a significant paper in that it presents a valuable method of investigating topographical effects. Furthermore, this was one of the first investigations of the diffraction of N-waves by buildings.

P-113
SONIC BOOM MODELING INVESTIGATION OF TOPOGRAPHICAL AND ATMOSPHERIC EFFECTS
A. B. Sauer and C. J. Bagley
FAA-NO-70-10, July 1970

The results of an experimental program whose purpose was to study the effects of topographical and structural shapes on sonic boom focusing and to study the effects of atmospheric turbulence on sonic boom signatures are presented in this paper. These effects were modeled by firing projectiles and by allowing the projectile N-waves to interact with model shapes and with turbulent jets. The wave interactions were studied by means of shadowgraph pictures and microphone pressure records. Turbulence scaling parameters are developed and used to relate the model results to full scale.

The following conclusions were reached as a result of this investigation:

(1) Boom focusing will usually occur in structural shapes having interior corners, but almost any sort of shielding of the corners will reduce the focusing effect.

(2) Boom focusing effects depend on the direction of the incident wave with respect to the structure or topographical shape.

(3) Large canyons and similar shapes can cause strong focusing of booms, but large focusing effects will occur only for rather specialized shapes and particular directions of the booms. The influence factors (defined as the ratio of the reflected sonic boom amplitude to the free air amplitude) may be of the order of 12 or greater.

(4) The influence factor (IF) for a plane, rigid surface is 2. This serves as a standard for evaluating other shapes.

(5) The maximum IF of a two-dimensional structure with right-angled corners is 4.

(6) Corner structures having a solid angle of $\pi/2$ can have an IF as large as 8; larger IF's are found with smaller solid angles.

(7) Irregularities in the above structures or topographical shapes will reduce the IF.

(8) Because of wave reflections, the topographical models usually increase the duration of the boom by a factor of two or more as compared to the [illegible] of a plane rigid surface.

(9) The peak IF is found at the inside corner of models such as step or overhang models; as one goes away from this corner the maximum IF falls off somewhat if the signature length is long compared to the distance from the corner. When the signature length is of the same order as the distance from the corner, the maximum IF tends to be greatly reduced.

(10) The theory of Crow (see capsule summary P-79) explains the essentials of boom signature fluctuations in a turbulent atmosphere, but the mechanisms of the shock front breakup and of certain nonlinear features are not yet understood.

(11) The boom signature fluctuations depend primarily on the height δ of the atmospheric boundary layer, the distribution of turbulence intensities u', and the turbulent spectral energy distribution and related integral scale L. Mean velocity and temperature gradients will also affect the fluctuations.

(12) Atmospheric shear layers cannot be studied alone for their effect on boom signatures because such shear layers always generate turbulence which affects the signatures.

(13) The boom signature fluctuations can be better understood by obtaining a larger number of data shots and by a more detailed study of the statistical data. The fine scale spiky structure can be studied on a larger scale by increasing the turbulence intensities u' and by increasing the turbulent layer thickness δ. This larger scale is needed so that no fine structure might be overlooked because of limitations in microphone response to high frequencies.

(14) The experiments clearly show that the signature perturbations observed near the leading N-wave shock are repeated near the trailing N-wave shock; this result agrees with full-scale observations and is explained in the Crow theory by the "freezing" of the turbulence during the short passage time of the N-wave.

In another investigation conducted at about the same time Brooks, Beasley, and Barger (see capsule summary P-112) used a spark-generated N-wave to investigate the diffraction and reflection of sonic booms by buildings. The results were qualitatively much the same as those of the present investigation. Diffraction effects were not dealt with in the present paper but the overpressures were determined much more accurately than in the other investigation.

This was one of the first controlled experimental investigations into the effects of turbulence on sonic booms. In flight-test experiments the turbulent properties of the atmosphere cannot be determined very accurately, and this makes it difficult to correlate theory and experiment. The controlled turbulence levels of the present investigation made such a correlation much easier.

P-114

SERIES EXPANSION FOR THE SOUND FIELD AT A CAUSTIC

D. A. Sachs

Cambridge Acoustical Associates, Inc.,

Technical Report U-363-222, Sept. 1970

This paper presents a derivation of higher order terms in a series expansion of the sound field in the vicinity of a caustic. The results are applicable to a caustic zone in an arbitrarily stratified medium at which sound energy from a time-harmonic point source is focused. The higher order terms can be used either to extend the range of applicability in the frequency domain of the lower order terms or to provide an estimate of their validity. As an example of the application of the correction terms, the accuracy of the first-order solution is studied on the caustic formed by a point sound source immersed in a medium with a bilinear sound speed profile. It is found that the first order solution's accuracy improves with increasing frequency and decreases with increasing sound speed gradients and distance from the turning point of the ray passing through the caustic point.

In related work, Hayes (see capsule summary P-91) gave a brief treatment of nonlinear acoustic propagation through a caustic. Myers and Friedman (see capsule summary P-59) used linear theory to treat the topic of ray focusing.

Although it was done for continuous sound sources, the present work may have some application to the sonic boom phenomenon at a caustic, which is an example of an impulsive sound source.

P-115

ATMOSPHERIC REFRACTION AND REFLECTION IN SONIC BOOMS

C. Thery

NASA TT F-13, 409, Dec. 1970

This paper presents an analytical method for predicting the atmospheric refraction of weak shock waves. The method of characteristics is applied successively to steady flight situations for refraction of a wave train in a two-dimensional atmosphere and for refraction of a wave in an atmosphere which has a rotational symmetry around the trajectory of the aircraft. The computing process used allows the wave refraction to be followed step by step as long as the flow behind the wave stays supersonic.

A differential equation which relates the variation of weak shock wave intensity to the incidence of the wave is integrated numerically to obtain curves which show the angle of incidence versus altitude. Also, the behavior of the shock wave in the vicinity of the region where the flow behind the shock is sonic is discussed.

This paper is a summary of previous papers by Thery and Auriol. As a result, most of the equations used are not derived but are merely stated. This makes the paper difficult to follow in places.

P-116

TROPOSPHERIC AND TURBULENT CONTRIBUTIONS TO SONIC BOOMS

R. F. Dressler

The Aeronautical Research Institute of Sweden

FFA Rpt. 121, Stockholm, 1970

The purpose of this paper is to assess the relative importance of tropospheric versus ground-layer contributions to sonic boom magnifications. This is done through a statistical analysis of the data obtained in the Oklahoma flight tests of 1964. The ground-layer contribution is due to the layer of turbulent air usually present between ground and about 2000-3000 feet, and

the tropospheric contribution is that due to strong winds plus the large-scale temperature deviations from "standard" profile, both usually present in the troposphere.

Data from 628 flights is analyzed. These flights were all made along the same flight path. The altitudes of these flights were within the range 23,000-37,000 feet and more than 90% were within the range 28,000-32,000 feet. It is stated by the authors that for such small variation, calculations show that only a negligible variation will be introduced. All flights were at Mach numbers greater than 1.4 and 475 flights were at $M = 1.5$. In performing the statistical analysis, no differentiation was made between flights at different Mach numbers and altitudes.

The basic procedure was as follows: For each flight the measured on-track overpressure ΔP_m and the calculated nominal ΔP_n were used to calculate the magnification ratio $\Delta P_m/\Delta P_n = M$. The M's for every flight were then plotted, grouping each day separately. In order to permit the addition of random variables instead of multiplication and to guarantee that the resulting distributions would be gaussian over most of their range, the logarithm of each M was taken. The large-scale tropospheric parameters were considered to be statistically constant during each daily testing interval, since the average time-span for the large-scale tropospheric parameters was considerably longer than the time interval (five hours or less) during which all flights per day in the data were flown. On the other hand, the detailed turbulent patterns change significantly from moment to moment and point to point. Since the flight path and direction were constant for every flight used, the contribution to total M from the large-scale effects was taken to be essentially constant for all flights during any one day. For this reason, the scatter in total M observed during any one day was taken to be due only to the variable turbulent structure. The variation of the daily mean of the magnification factor from day to day was assumed to be due only to large-scale tropospheric effects. The standard deviation of the difference between each measured value and the mean for that day (due to the turbulent contribution) was then compared with the standard deviation of the daily means (tropospheric contribution), and the following conclusions were reached.

(1) The standard deviation due to the large-scale (tropospheric) contribution is 40% as large as that from the overall turbulent (ground layer) contribution, when cruising altitudes average only 30,000 feet. As the former must increase with propagation path length (cruising altitude), while the latter remains constant, an assumed linear extrapolation would indicate that at high SST-cruising altitudes, both effects will become approximately equal. This extrapolation implies that a doubled overpressure ($M = 2$) would occur about four times more frequently with SST altitudes than observed in the Oklahoma tests. It is concluded that large-scale tropospheric effects on magnification are of definite significance above about 20,000 feet and cannot be neglected.

(2) The standard deviation for the turbulent contribution varied over an extremely wide range (7 to 1) for individual test days. This wide variation would make it possible to "prove" that the sonic boom is either "negligible" or "intolerable" by choosing a specific testing day and locality. Because of this, it is pointed out that much care must be used in drawing conclusions from flight test results.

In an earlier paper (see capsule summary P-61) Dressler and Fredholm made a theoretical investigation of the scatter in overpressure magnification due to large-scale atmospheric effects. No experimental data was used in that paper, in contrast to the present paper.

The present paper has two main weaknesses:

(1) The data sample was limited to airplane altitudes of 30,000 and 38,000 feet, which is not sufficient for extrapolations to higher altitudes such as 60,000 and 80,000 feet. The data used were obtained by airplanes flying in the influence of the jet stream winds which can vary significantly from day to day.

This would influence the airplane ground speed and hence the boom magnitude. The effect noted by the author cannot be extrapolated to higher altitudes because that kind of wind velocity does not exist there. Additional large data samples (see for instance Figure 1, page 352, NASA SP-255) for the XB-70 at 60,000 feet show less scatter than the F-104-produced data at 30,000 feet and 38,000 feet.

(2) Attributing the variation of the mean daily magnification factor from day to day strictly to tropospheric effects is very questionable. The amount of turbulence also varies from day to day. Thus it is possible that the daily variation of the mean magnification factor may be due partially or wholly to turbulence effects also.

P-117
METEOROLOGICAL EFFECTS ON THE SONIC BANG
J. M. Nicholls
Weather, London, Vol. 25, 1970, pp. 265-271

This paper gives a very brief survey of atmospheric effects on sonic boom propagation. Topics discussed are: (1) accelerating flight; (2) effects of vertical gradients of wind and temperature; (3) cut-off Mach number; and (4) the effects of other meteorological phenomena such as gravity waves, convective cells, and turbulence. These subjects are all treated very lightly.

This is a good introductory paper for a reader who knows very little about atmospheric effects on sonic booms.

P-118

ON THE EXPERIMENTAL DETERMINATION OF THE NEAR-FIELD BEHAVIOR OF THE SONIC BOOM, AND ITS APPLICATION TO PROBLEMS OF N-WAVE FOCUSING

D. J. Collins

AIAA Paper No. 71-185, Jan. 25-27, 1971

This paper presents the results of a ballistic range test whose purpose was to study the near-field behavior of the sonic boom generated by non-lifting, axially symmetric projectiles in a homogeneous atmosphere and to investigate diffraction and focusing of N-waves by obstacles. The reader is referred to capsule summary G-80 for a discussion of the near-field sonic boom results found in this investigation. The results concerning N-wave focusing and diffraction deal with sonic boom propagation and, therefore, are discussed here.

The measurements described in this report were obtained in a free-flight ballistics range constructed in the Guggenheim Aeronautical Laboratory at the California Institute of Technology. The concave corner models used in these experiments were constructed from matched pairs of steel and aluminum blocks, differing in both height and length, in order to determine the effect of these parameters on the focused shock wave. The measurements of the diffracted shock wave were obtained by using two rectangular steel plates, standing vertically on the ground plane.

A simple geometrical theory is developed to account for the intensification of an N-wave by a concave corner. This theory is based upon the assumption that all reflections are regular, i.e., that the angles of incidence and reflection are equal. It is also assumed that the shock waves are weak, thus making the problem linear. For the case of a plane wave incident symmetrically on a concave corner, the theory shows that

$$\frac{\Delta P_c}{\Delta P_f} > \frac{4\pi}{\beta}$$

where

ΔP_c = pressure jump after reflection from corner

ΔP_f = free-air pressure jump

β = angle of corner.

For the case where the incident wave moves parallel to one of the walls the theory gives

$$\frac{\Delta P_c}{\Delta P_f} > \frac{2\pi}{\beta}$$

A comparison of the results of this theory with experimental results shows good agreement for concave corner angles $\beta > \pi/2$. For $\beta < \pi/2$, the geometrical theory is inadequate as formulated, and must include the effects of diffraction of the wave by finite bodies. The experimental results show that the peak pressure rise occurs for a concave corner angle $\beta = \pi/4$, and is a function of both the obstacle height and the length of the corner walls. The maximum measured pressure was $\Delta P_c/\Delta P_f = 10.25$.

From the results of the measurements of the diffraction of an N-wave by the back corner of an obstacle, it is concluded that the approximate theory by Whitham (see capsule summary P-17), modified by Skews ("Profiles of Diffracting Shock Waves," Report No. 35, April, 1966, University of Witevatersrand, Johannesburg, South Africa) to calculate the shock wave position along characteristics rather than rays, and to more accurately reflect the angle between the characteristics and the rays, gives an adequate representation of the shock wave profile for shock Mach numbers near unity. The maximum pressure jump at the wall, relative to the free-wave value, is given by $\Delta P_{max}/\Delta P_{free} = 0.48$.

In a previous investigation (see capsule summary P-112) Brooks, Beasley, and Barger used a spark-generated N-wave to investigate the focusing and diffraction of an N-wave by buildings. The overpressures were not measured very precisely, and, as a result, the results were more qualitative than those of the present investigation. In another investigation Bauer and Bagley used projectiles fired in a ballistic range to investigate topographical effects on sonic booms. They did not consider diffraction effects, but their results concerning focusing effects are in fairly good agreement with those of the present paper.

The area in which the present paper excels, in comparison to the two earlier investigations discussed above, is in its attempt to correlate experiment and theory. The earlier investigations were concerned primarily with obtaining experimental results, while the present paper places equal emphasis on theory and experiment.

P-119

STUDY COVERING CALCULATIONS AND ANALYSIS OF SONIC BOOM DURING OPERATIONAL MANEUVERS

G. T. Haglund and E. J. Kane

Boeing Document D6A12108-1 Vol. I, Analysis and Computation of Maneuver Effects

Vol. 1 of DCT Report No. EQ-71-2, Feb. 1971

This is the first volume of a three volume study concerning the effects of operational SST maneuvers on sonic booms. The method developed by Hayes, Haefeli, and Kulsrud (see capsule summary P-98) is used to perform this investigation. Included are the effects of longitudinal accelerations, pullups, pushovers, and turns in several different atmospheres. The effects of various airplane altitudes, Mach numbers, load factors, weights, accelerations, climb angles, and atmospheric conditions are also presented. Two different SST-class airplanes are used in the study, the U.S. SST and the SCAT 15-F (an SST concept developed at the NASA Langley Research Center).

The results are made to be independent of the airplane characteristics by the use of sonic boom pressure scaling factors. The scaling factors are used to scale a steady, level pressure signature for a specific airplane flight condition to obtain the complete sonic boom pressure signature for the maneuver effects. Two scaling factors are used, one to scale the

intensity and another to account for the non-linear distortion which causes the formation and merging of shocks. Extensive tabulations are made in the appendices of the quantities necessary to calculate these scaling factors for various maneuvers and flight conditions. These scaling factors can be used to determine maneuver effects for any specific airplane (given the airplane F-function or steady, level pressure signatures). They are also ideally suited to obtaining rapid estimates of the maneuver effects on sonic boom intensities.

The following conclusions were reached as a result of this investigation:

1. The effects of SST operational maneuvers on sonic boom at the ground are small except at Mach numbers below about Mach 1.3 and for turn maneuvers where significant effects can occur up to Mach 3.

2. Caustics can be produced at the ground during longitudinal accelerations and pushover maneuvers for operational load factors at the low supersonic Mach numbers only ($M < 1.3$). During turns, caustics at the ground may be produced at Mach numbers up to 3; the caustics occur near the edge of the boom carpet, however, well to the side of the flight path. Methods for calculating maneuver requirements for caustics at the ground are presented and the results are summarized in graphic form.

3. Longitudinal accelerations result in slightly longer pressure signatures with stronger shock waves. During pullups the pressure signature increases in length and the shock waves are weaker compared to steady, level flight. The opposite is true, in general, for pushover maneuvers. The airplane climb angle has an important effect on shock wave strength during pullups and pushovers. These effects are small for operational maneuvers except at the low supersonic Mach numbers. Turn maneuvers result in a variety of pressure signature types at the ground, since a caustic generally occurs to one side of the airplane, while on the other side of the airplane a large region of low intensity sonic boom occurs.

George and Plotkin (see capsule summary P-106) derived scaling factors C_T, C_A, and C_I that are analogous to the intensity and age scaling factors, S_1 and S_2, presented here. They can be used to determine complete sonic boom signatures in a still, stratified atmosphere directly below an airplane in steady, level flight without the use of a computer. The method used by George and Plotkin, however, is slightly different from the method used here. They scale a ΔP wave at a reference altitude, r_h, below the airplane (about 500 feet), while in the method used here the F-function itself is scaled. When this difference is taken into account, the two methods give the same results.

In a similar investigation (see capsule summary P-97) Haefeli conducted a study to determine the effects of selected atmosphere, wind, and airplane maneuvers on sonic boom pressure signatures for the F-104 and the SCAT 15-F. One of the major conclusions of that study was that the effects of airplane maneuvers on sonic boom pressure signatures are not independent of airplane type, so that the maneuver effects must be determined separately for each specific airplane type, airplane weight, and airplane load factor. The present study overcomes this limitation by making the results independent of the airplane characteristics through the use of the sonic boom pressure signature scaling factors. The use of the scaling factors for presenting the maneuver effects makes the results of this study much more useful than those of previous studies.

P-120

STUDY COVERING CALCULATIONS AND ANALYSIS OF SONIC BOOM DURING OPERATIONAL MANEUVERS
G. T. Haglund and E. J. Kane
Boeing Document D6A12108-2 Vol. II, Preliminary Flight Test Plan
Vol. II of DOT Report No. EQ-71-2, Feb. 1971

This is the second volume of a three volume study concerning the effects of operational SST maneuvers on sonic booms. Volume I shows that the theoretical effects of operational maneuvers due to typical SST maneuvers are small except for maneuvers at Mach numbers below about 1.3. Methods are outlined for applying the results to any airplane, and selected pressure signatures are presented for the U.S. SST and SCAT 15-F. The reader is referred to capsule summary P-119 for further details of Volume I. Volume III describes the modifications made to the computer program developed by Hayes (see capsule summary P-98) to improve its capability for use in the present study. See capsule summary P-121 for further details of Volume III. The present volume contains a flight test plan designed to investigate caustics at the ground produced during longitudinal accelerations, circular turns, and steady, level flight at the threshold Mach number. In addition to the flight test plan, flight test aids are presented to be used in the field as aids in positioning the test airplanes so that caustic phenomena are observed over the micro[illegible] network. The flight test aids account for variations of atmospheric temperature, winds, and flight variables such as airplane altitude and Mach number.

The following conclusions were reached with regard to the flight test plans presented here:

(1) The method of geometric acoustics is adequate for calculating caustic locations and lateral cutoff locations.

(2) The accuracy of the operational flight test aids in placing the caustic in the desired location is as follows:

Threshold Mach number flight: ±[illegible] ft. in altitude

Lateral cutoff location: ±1.0 st. mi.

Caustic location due to longitudinal acceleration: ±1.5 st. mi.

Caustic location due to a turn: ±1.5 st. mi.

(3) The tolerance in the prediction of the lateral cutoff location and the caustic location due to longitudinal acceleration can be reduced to less than 1 st. mi. by using computer programs and measured real-time atmospheric data.

Caustics are among the least-understood of all sonic boom phenomena. There have been several attempts to calculate theoretically the pressure rise at a caustic (see capsule summaries P-59 and P-91, for example). The evaluation of these and future theories will depend upon a comparison with accurate experimental results, and the present paper will be a great aid in obtaining such results.

P-121

STUDY COVERING CALCULATIONS AND ANALYSIS OF SONIC BOOM DURING OPERATIONAL MANEUVERS
G. T. Haglund and D. L. Olson
Boeing Document D6A12108-3 Vol. III, Description of Computer Program "Sonic Boom Propagation in a Stratified Atmosphere" and Estimation of Limitation Near Caustics
Vol. III of DOT Report No. EQ-71-2, Feb. 1971

This is the third volume of a three volume study concerning the effects of operational SST maneuvers on sonic booms. Volume I shows that the theoretical effects of operational maneuvers due to typical SST maneuvers are small except for maneuvers at Mach numbers below about 1.3. Methods are outlined for applying the results to any airplane, and selected pressure signatures are presented for the U.S. SST and SCAT 15-F. The reader is referred to capsule summary P-119 for further details of Volume I. Volume II contains a flight test plan designed to investigate caustics at the ground produced during longitudinal accelerations, circular turns, and steady, level flight at the threshold Mach number. See capsule summary P-120 for further details of Volume II.

In the present volume the comprehensive computer program developed by Hayes (see capsule summary P-98) is modified to improve its capability. The basic theory is summarized briefly and all modifications are documented in detail. These modifications included improvement of the method for inputting the airplane F-function, addition of the capability to compute up to twenty sonic boom signatures per ray without redoing the ray calculations, development of a method to account for a wind shear discontinuity, addition of the capability to compute the atmosphere parameters using the Hypsometric equation, derivation of a caustic warning parameter, addition of automatic plotting of the complete sonic boom pressure signatures, and improvement of the input/output scheme (including files on magnetic tapes for storing various input data). Detailed instructions on use of the program are given, and a sample set of input data with corresponding results from the program are presented. Also, the program design, structure, and logic are described in detail along with a brief description of the purpose, method, inputs/outputs, etc., of each subroutine. A complete listing of the FORTRAN IV source deck is included in Appendix B.

The computer program developed by Hayes, Haefeli, and Kulsrud was a great improvement over previous methods, mainly because it took into account airplane maneuvers and near-field effects. The improvements to this program made in the present paper increase its capability and economy. Thus these improvements are important contributions to an already valuable portion of sonic boom theory.

P-122

MEASUREMENTS OF THE REFRACTION AND DIFFRACTION OF A SHORT N-WAVE BY A GAS-FILLED SOAP BUBBLE
Bruce A. Davy and David T. Blackstock
The Journal of the Acoustical Society of America, Vol. 49, No. 3 (Part 2), 1971, pp. 732-737

In the investigation discussed in this paper a spark-generated N-wave was refracted and diffracted by a gas-filled soap bubble and the resulting waveform measured. The purpose of this experiment was to test Pierce's proposal (see capsule summary P-80) that the peaking and rounding observed on sonic boom press[illegible]signatures is due to refraction and diffr[illegible] caused by atmospheric inhomogeneitie[illegible]ording to this theory, the low-frequenc[illegible]nents of the N-wave will be diffracted around the inhomogeneity and reach the observer relatively unchanged. The high-frequency components, however, will either be focused or defocused, depending upon whether the lens has converging or diverging properties, respectively. In this experiment the bubble acted as a converging lens when filled with argon and as a diverging lens when filled with helium.

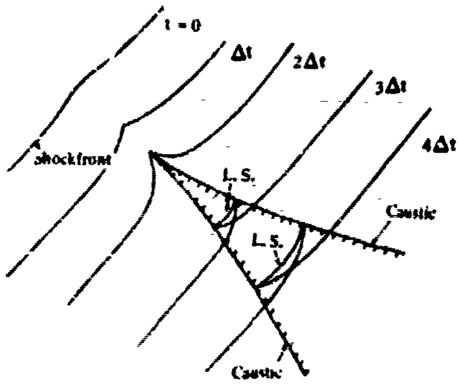
It was found that the argon lens caused a substantial peaking of the wave, the peaked wave amplitude being about three times that of the unobstructed control wave. Conversely, the helium-filled bubble was found to be very effective in rounding off the shocks. These results, however, only qualitatively support Pierce's theory, since many of the particular conditions assumed by Pierce were not reproduced in this experiment. Pierce chose an inhomogeneity mild enough so that the diffracted and refracted signals had nearly equal arrival times and comparable amplitudes. In the present experiment neither of these conditions was met. Furthermore, the finite size of the microphone made an exact interpretation of the results very difficult, since it was expected that the waveform on the axis might be quite different from that observed off the axis.

In spite of its limitations, the present investigation was the first controlled experiment to demonstrate the plausibility of Pierce's theory.

P-123
STATISTICAL THEORY OF ATMOSPHERIC TURBULENCE EFFECTS ON SONIC-BOOM RISE TIMES
A. D. Pierce
The Journal of the Acoustical Society of America, Vol. 49, No. 3 (Part 2), 1971, pp. 906-924

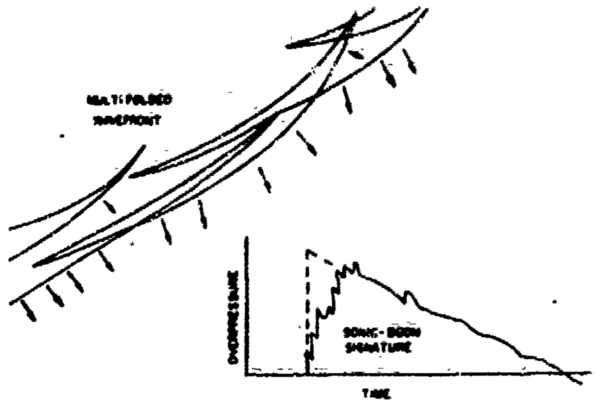
A theory is presented in this paper which attempts to explain the anomalously large rise times of sonic boom pressure signatures. According to theory, these rise times should be on the order of 10-80 μsec. However, observed rise times are typically about 5 msec. The theory presented here attempts to explain this disparity in terms of a wavefront-folding mechanism.

The theory is based upon the assumption that a shock front develops ripples as it propagates through regions of atmospheric turbulence. These ripples are, according to geometric acoustics, subsequently transformed to folds in the front when the shock passes vertices of caustics, as shown in the figure below, which was taken from this paper.



Wavefront-Folding Mechanism

According to the theory, the process of wavefront folding may occur many times, providing that the strength of the small-scale turbulence is sufficiently great, up to once for each inwardly concave ripple that develops along the shock front. A sketch of such a multi-folded shock front is shown in the figure below, which was taken from this paper. Thus an observer at a far-field point would notice many segments of the folded front pass by. This could lead to the type of signature shown in the figure below which is composed of a large number of discrete pressure jumps (called microshocks by the author). The net effect is a waveform with an anomalously large rise time. Each jump in this signature corresponds to a segment of the folded wavefront. It is hypothesized that the effects of viscosity would tend to smear out the fine structure.



Multifolded Shock Front and Possible Signature

A mathematical model is then developed which describes such a process. The model is dependent upon the statistics of the turbulence through three parameters, one of which is Crow's characteristic time t_c (see capsule summary P-79). An analysis is made, based on the model, which substantiates the supposition that typical waveforms are composed of many very small discrete microshocks. An expression for the ensemble average of the early portion of the ground-level signatures is derived for which the corresponding rise time is found to be of the order of $(2 \text{ to } 3)t_c$ (Crow estimated t_c to be about 0.7 msec). This gives a rise time of about 2 msec, which is in reasonable agreement with measured data. It is shown that nonlinear effects, while not necessarily negligible, are insufficient to nullify the mechanism.

Although the mechanism of wavefront folding appears to be very plausible, the conclusion that wavefront folding is the primary cause of anomalous rise time remains tentative because of the many approximations employed in the analysis.

In a later paper (see capsule summary P-124) George and Plotkin propose a theory which explains sonic boom rise times in terms of reaching a balance between nonlinear steepening effects and a dissipative mechanism due to acoustic scattering of high frequency energy out of the incident wave direction. However, neither that theory nor the theory of the present paper has been verified experimentally. There have been two experimental investigations and one theoretical paper which indicate that the wavefront-folding mechanism may have some validity, however. In the first experimental investigation Beasley, et al. (see capsule summary P-102) used spark-generated N-waves to investigate focusing of weak shock waves. They found that weak shocks (about 2 psf) obeyed the laws of geometrical acoustics when passing through a focus, which is in agreement with the supposition of the wavefront folding theory. In the second experimental investigation, Maglieri, using an array of ground microphones to determine the shape of a sonic boom shock front, found evidence confirming the presence of ripples in the wavefront (see capsule summary P-36). And, finally, in an analytical investigation Parker and Zalosh (see capsule summary P-161) showed

that realistic atmospheric temperature inhomogeneities can be expected to result in focusing factors of 2 or less.

Thus, even though the complete theory of the present paper has not yet been experimentally verified, the basic hypotheses of the theory have been shown to be very plausible.

P-124
PROPAGATION OF SONIC BOOMS AND OTHER WEAK NONLINEAR WAVES THROUGH TURBULENCE
A. R. George and K. J. Plotkin
The Physics of Fluids, Vol. 14, No. 3, March 1971, pp. 548-554

The structure of weak shocks propagating over long distances through turbulence modeled by sound speed fluctuations is investigated in this paper. The equations of continuity, entropy, and momentum for an inviscid compressible fluid are used and the pressure is expanded in a perturbation series. This results in a system of equations of various orders which are used to obtain a single equation for the wave structure. It is shown that the equilibrium wave shape is governed by a balance between nonlinear steepening and a dissipative mechanism due to acoustic scattering of high frequency energy out of the incident wave direction. This scattered energy appears as perturbations arriving behind the shock. For conditions representative of sonic boom and explosion waves propagating over long distances it is shown that the equation governing the wave structure reduces to the following Burgers' equation, which is similar to that describing viscous shocks, the difference being that parameters describing the turbulent scattering appear in the dissipative term:

$$\frac{\partial P}{\partial t} + \frac{\gamma + 1}{2\gamma} \frac{a_\infty}{P_\infty} P \frac{\partial P}{\partial X} = \epsilon^2 L_o a_\infty \frac{\partial^2 P}{\partial X^2}$$

where P is the wave structure with first scattered waves removed, a_∞ and P_∞ are mean ambient sound speed and pressure, X is the wave fixed coordinate, ϵ^2 is the turbulent intensity, and L_o is the turbulent macroscale length. It is then shown that the theoretical predictions resulting from this equation agree in order of magnitude with experiments on atmospheric propagation of sonic boom and explosion waves.

Crow (see capsule summary P-79) made an analysis based on first order scattering theory which showed that many of the characteristics of the random perturbations of the observed waves could be predicted by turbulent scattering. He considered the perturbations caused by a discontinuous shock wave. His results, therefore include scattering from very high-frequency components in the incident wave. However, his theory predicts very strong scattering for high frequencies. As a result the generally reasonable predictions become enormous near the shock wave where the observed perturbations reach a finite maximum. It is shown in this paper that in order to correctly predict the maximum mean square fluctuations the thickened shock structure must be included. Crow noted this and surmised that a second order theory would be necessary. The present paper investigates this thickened shock structure and shows it to be due to strong turbulent scattering of high-frequency components.

This was one of the first attempts to explain the fact that the thicknesses of the shocks associated with sonic booms are of the order of 10^3 times that which is predicted by conventional shock structure based upon ordinary viscosity and heat conduction.

P-125
DIFFRACTION OF A PULSE BY A THREE-DIMENSIONAL CORNER
Lu Ting and Fanny Kung
NASA CR-1728, March 1971

This is an extensive theoretical investigation into the diffraction of a pulse by a three-dimensional corner. The following results are obtained in this paper:

1. The conical solution for the diffraction of a plane acoustic pulse by a three-dimensional corner of a cube is obtained by separation of variables.

2. A systematic procedure is presented such that the eigenvalue problem is reduced to that of a system of linear algebraic equations. Numerical results for the eigenvalues and functions are obtained and applied to construct the conical solution for the diffraction of a plane pulse.

3. The numerical results suggest that the eigenvalues for corners can be approximated, one by one, by the eigenvalues for circular cones of the same solid angle.

4. "Mean-value" theorems are derived for solutions of wave equations so that the resultant wave at the vertex of a cone can be related to the incident wave or the value at the vertex of a different cone. These theorems are useful to extend the knowledge of the conical solutions to the adjacent corners or edges.

Relevant numerical programs for the analysis are presented in the appendix.

In addition to being useful in following the propagation of sonic booms, these results would be of use in analyzing the effect of booms on structures and terrain.

P-126
SONIC BOOM AND TURBULENCE INTERACTIONS -- LABORATORY MEASUREMENTS COMPARED WITH THEORY
A. B. Bauer
AIAA Paper No. 71-618, June 21-23, 1971

In this investigation a ballistic range was used to fire projectiles for generating laboratory-scale sonic booms. The boom signatures were recorded by means of two microphones after the signature wave forms were modified by traveling through turbulence in a large jet of air. The signatures showed the random and spiky nature that has been measured from full scale sonic

booms. More than 600 signatures and shadowgraphs of the shock structure were recorded. Jet turbulence measurements were used with the theoretical formulation of Crow (see capsule summary P-79) to predict statistical results which are compared with a statistical analysis of the signatures.

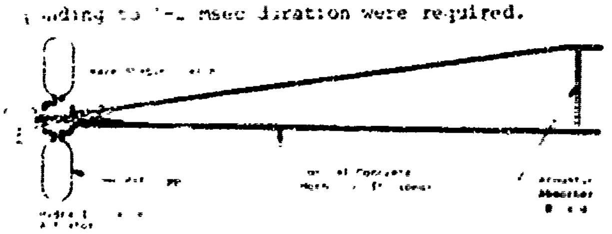
The results show that Crow's theory is in rough agreement with the measured pressure fluctuations. This rough agreement is all that was expected since, as stated by the authors, only an approximate comparison between experiment and theory was carried out here. This approximation was due to the approximate nature of the theories, the difficulties in making measurements, and the random nature of turbulence.

This paper is very similar to the latter portion of an earlier paper by Bauer and Bagley (see capsule summary P-113). The reader is referred to that capsule summary for additional details of this work.

P-127
EXPERIMENTAL INVESTIGATION OF N-WAVE INTERACTION WITH TOPOGRAPHIC MODELS
J. Peschke
AIAA Paper No. 71-619, Presented at AIAA 4th Fluid and Plasma Dynamics Conference, Palo Alto, Calif., June 21-23, 1971

The results of an experimental program conducted to study the time history of the surface pressure due to sonic boom interaction with several topographical configurations are presented in this paper. The purpose of the experiments was to validate the predictions of acoustic theory for simple configurations and to demonstrate that the NASA/GASL (General Applied Science Laboratories) sonic boom simulator could be used to provide surface pressure data for topographic geometries which are not readily amenable to theoretical treatment.

The NASA/GASL sonic boom simulator is shown, schematically in the figure below, which was taken from this paper. The three major components of the facility are the mass flow control valve, a square cross-section conical duct, and an absorber located at the duct termination. The concept of operation is based on a controlled gas mass flow through a sonic orifice located at the origin of the conical duct. The facility can be operated in two modes: for short duration sonic boom signatures (1-5 msec), a diaphragm burst is used to discharge the air contained within the plenum chamber, whereas long duration waves are generated by a prescribed regulation of mass flow rate obtained by varying the [illegible] of the valve. The diaphragm mode of operation was employed for the studies reported here, since scaled wave lengths corresponding to [illegible] msec duration were required.



Schematic of the Sonic Boom Simulator

The various topographical configurations investigated include step, corner, overhang, cavity, and two-building models. Simple acoustic theory was used to predict the wave shape and intensity resulting from reflections from each of these models. Each model was then placed in the sonic boom simulator and the measured signatures were compared with the predicted signatures. The results showed good correlation between the measured and predicted pressure signatures. Specifically, good agreement with the results of the theoretical treatment by Ting and Kung (see capsule summary P-149) was obtained. The table below summarizes the predicted and measured intensification factors (ratio of maximum overpressure after wave has interacted with topographic model to free stream maximum overpressure) for each of the configurations.

CONFIGURATION	INCIDENCE ANGLE DEGREES	PREDICTED I.F.	MEASURED I.F.	MEASURED OVERPRESSURE-psf
90° Step	0	2.0	2.0	[illegible]
	45	[illegible]	[illegible]	11.0
90° Corner:				
Concave Corner	0	4.0	4.0	12.0
Concave Corner	45	8.0	[illegible]	[illegible]
45° Corner:				
Concave Corner	0	8.0	[illegible]	[illegible]
Concave Corner	45	16.0	[illegible]	[illegible]
Sphere	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]		[illegible]	[illegible]
		[illegible]		
	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]		[illegible]	[illegible]
		[illegible]		
Cantilever/ [illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]		
	[illegible]		[illegible]	[illegible]
		[illegible]		
Parabolic [illegible]	0		[illegible] approx	[illegible]
	15	[illegible]	[illegible] approx	[illegible]
Two Buildings	[illegible]	[illegible]	[illegible]	[illegible]

Predicted and Measured Intensification Factors

It is concluded that the acoustic horn ground facility is an appropriate tool for the investigation of complex configurations for which theoretical treatment is limited.

In a previous investigation Brooks, Beasley, and Barger (see capsule summary P-112) used a spark-generated N-wave to investigate diffraction and reflection of sonic booms by buildings. However, their overpressure measurments were not very accurate and only qualitative conclusions were reached. These conclusions were, for the most part, in agreement with those of the present investigation. The one exception was that Brooks, et al. predicted that diffraction effects would prevent the intensification factor from reaching 4 at the forward face of the building, in contradiction to the measured results of the present investigation.

Bauer and Bagley (see capsule summary P-113, used a ballistic range to investigate topographical effects on sonic booms. Their results agree quite well with those of the present paper.

This paper makes excellent use of illustrations. For each model the wave pattern predicted by theory is shown schematically, together with the microphone locations. Also shown is the theoretical pressure signature which would result

from such a wave pattern. Shown right next to this is the measured wave pattern, making a comparison between experiment and theory very easy for the reader.

P-128
MAXIMUM OVERPRESSURES OF SONIC BOOMS NEAR THE CUSPS OF CAUSTICS
A. D. Pierce
Noise and Vibration Control Engineering, Purdue, 1971, pp. 544-553

In this paper an approximate theory is presented for estimating the peak overpressure at a caustic cusp (also called an arete or a line of super-focalization). The important parameters of the analysis are shown to be: (1) the minimum radius of curvature R_o of the shock front some time before it reaches the cusp; (2) the second derivative R_o'' of the curvature radius with respect to transverse distance along the front; and (3) the peak overpressure ΔP_o at the point where R_o and R_o'' are measured.

An extensive mathematical model is developed which incorporates all of the various processes which take place at an arete. These include the overpressure magnification predicted by geometrical acoustics, diffraction effects, the increase of shock speed due to finite amplitude effects, the inherent dissipation at the shock front, and the stretching of the waveform.

The principal result of the analysis is that the greatest peak overpressure ΔP_{max} near an arete is of the order of

$$P_o(\Delta P_o/P_o)^{2/3}(R_oR_o''\cdot)^{1/3}$$

This is applied to the cases of superbooms resulting from maneuvers. It is concluded that the focus factor at a cusp varies with the nominally expected overpressure ΔP_{nom} as

$$(P_o/\Delta P_{nom})^{1/3}.$$

A check on the theory is then made using the experimental data of Wanner, et al. (see capsule summary P-155). For the particular case chosen (horizontal turning maneuver of Mirage IV aircraft at 36,000 feet and M = 1.7) the measured focus factor at the super-focus was 9. The calculated value, based on the theory of the present paper, was 7. It was felt that this agreement was fairly good, considering all of the approximations involved in the theory. However, further experimental verification of the theory is required to determine whether this agreement was fortuitous.

P-129
SONIC-BOOM CALCULATION IN A STRATIFIED ATMOSPHERE
M. Schorling
Noise and Vibration Control Engineering, Purdue, 1971, pp. 538-543

This paper is an extension of a previous paper by Schorling (see capsule summary G-55). That paper presented a second order solution for the case of a homogeneous atmosphere of the supersonic flow in the far-field of a slender lifting body with a nearly circular cross-section. That theory is extended in this paper to a stratified atmosphere in which the speed of sound, a, changes with the altitude, z, of the flight. The density, ρ, and pressure, p, are assumed to obey the hydrostatic law $dp = -\rho g dz$. The gas is considered to be nonviscous, homoenergetic, homentropic, and steady in the undisturbed field as well as in the disturbed flow field. Except for these assumptions, the method of solution is the same as that of the previous paper. The reader is referred to capsule summary G-55 for further details of this work.

P-130
METEOROLOGICAL MEASUREMENTS IN SUPPORT OF THE NASA GRAZING SONIC BOOM EXPERIMENT AT JACKASS FLATS, NEVADA
G. A. Herbert, A. Giarrusso
NOAA Technical Memorandum, ERL ARL-35, Aug. 1971

This report discusses the meteorological data measured in support of the NASA Grazing Sonic Boom Experiment at Jackass Flats, Nevada, and the manner in which these measurements were made. Sonic booms originating from aircraft flying at speeds comparable to the speed of sound at ground level were recorded on the ground and on the 460-m BREN tower on the Nevada Test Site. The propagation velocity of sound was determined by measuring the temperature, wind speed, and direction from the surface (3 m) to the aircraft flight altitude (10.3 km). These data were collected by rawinsondes, aircraft-mounted, and tower-mounted instrumentation. Profiles from these systems were compared in regions where the soundings overlap in time and space. Estimates of the rate of kinetic energy dissipation, an important parameter in determining the effect of atmospheric turbulence on weak shocks, were computed from airborne and tower data. Atmospheric stability was calculated from average wind speed and temperatures measured on the Bren tower.

Hayes' computer program (see capsule summary P-98) was used to show that when the gradient of the propagation velocity in the lowest kilometer is small, the paths of rays generated at low Mach numbers pass close to local topographic features.

The meteorological measurements discussed in this paper are used by Haglund and Kane (see capsule summary P-162) in a later paper which contains an analysis of the measured sonic booms obtained in this experiment.

P-131
SONIC BOOM IN TURBULENCE
W. A. Horning
NASA CR-1879, September 1971

In this report the case treated from first principles is that of random overpressure peaks with maxima which exceed by an unusual amount the single pressure peak of a sonic boom in a smoothly varying atmosphere. The random pressure peaks are attributed to small temperature and velocity fluctuations in typical atmospheric turbulence. This attribution is supported by the agreement between the data and the

calculations. Errors in the basic analysis and numerical work are believed small compared to uncertainties about the turbulence at the times data were measured.

Gustiness near ground, in a layer of air from a few hundred to a thousand feet thick, may infrequently produce turbulence so strong that its effect on wave propagation outweighs that of all turbulence above that ground layer. The statistics of microflow in such unusually active ground layers are not well understood, nor does the present study treat their effect on sound. Barring such ground layers, the random pressure peaks observed in sonic boom are explained by the theory of the present paper, the authors believe.

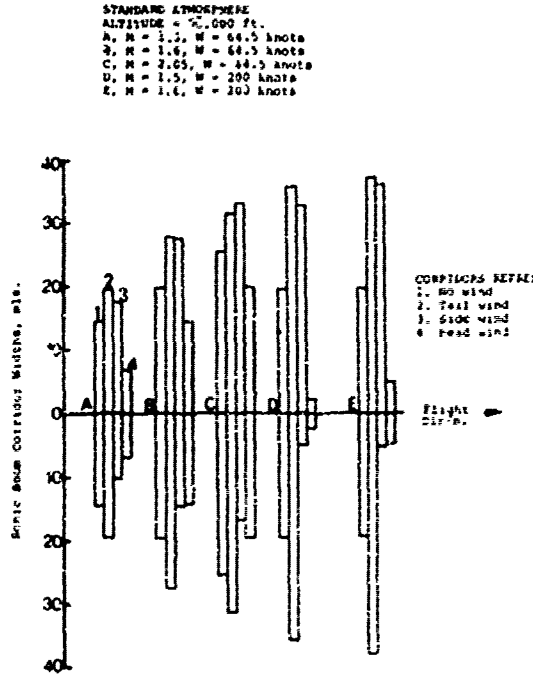
The analysis was influenced by the complexity of the wave scattering problem presented by a sonic boom in turbulence. This complexity arises largely because the N-shaped form of the dependence of overpressure on altitude contains a wide range of important component frequencies. It is a broad banded signal. Wave scattering by turbulence is a strong function of sonic frequency, with the highest important frequencies (10^4 Hz) randomized within a 10 meter length of wave path in a typical atmosphere near ground. This small pathlength for randomization requires multiple scattering in the quantitative analyses of boom statistics. The analysis used is a natural extension of the single scattering theory of Crow (see capsule summary P-79) whose conclusions have been verified more quantitatively.

The data presented by Garrick and Maglieri (see capsule summary P-81) is used to check the theoretical predictions of the present paper. It is found that the computed results are in general agreement with the data.

P-122
THE EFFECTS OF WIND AND TEMPERATURE GRADIENTS ON SONIC BOOM CORRIDORS
P. O. Onyeonwu
UTIAS Technical Note No. 168, AFOSR-TR-71-3087, Oct., 1971

A calculation of sonic boom corridors based on closed form solutions of the ray acoustic equations (see capsule summary P-95) using piecewise linear atmospheric models of winds and temperatures is presented in this paper. Detailed solutions of ray tracing equations are presented for all possible variations of winds and temperatures, within the framework of the assumed horizontally stratified model atmosphere. The effects of aircraft flight altitude and Mach number, wind and temperature gradients, and wind direction on sonic boom corridor are investigated in detail, including the effects of non-standard atmospheres such as prevail in winter months.

The figure below is an example of the results obtained. This figure illustrates the effect of flight Mach number and wind speed on sonic boom corridors. In this figure five groups of corridors (length of each strip represents corridor widths; width of each strip is non-dimensional) labelled A, B, C, D, E are shown. Within each group, starting from the left and proceeding to the right, the strips represent no wind, tail wind, side wind (blowing from right of flight path to the left), and head wind, respectively. Several other figures of a similar nature are also presented in the paper.



Effects of Mach Number and Wind Magnitude on Sonic Boom Corridor

The following conclusions were reached as a result of this investigation.

(1) The results show that whereas a complete cut-off of sonic boom for flights above the tropopause in a quiescent standard atmosphere occurs for $M<1.15$, the cut-off Mach number is reduced by the tail wind. Specifically, a tail wind of about 87 knots will reduce the cut-off Mach number to $M = 1.0$ at the appropriate altitude within the tropopause.

(2) Theoretically, s[illegible]iciently high head winds will conf[illegible] the sonic boom to the flight track on[illegible] with attendant focusing effects; higher winds will cause boom cut-off. However, the required head winds increase with Mach number and exceed 200 knots above $M = 1.5$. The main effect of side winds is to shift the corridor laterally leeward with respect to the flight track, the shift being in proportion to the wind strength. Side winds less than 20 knots at 40,000 feet do not alter the width of the corridor from the no-wind case, but higher winds cause a slight reduction. In particular, a side wind of 200 knots at 40,000 feet causes a 13% reduction in corridor width from the no-wind case.

(3) It is found that for small to moderate wind profiles and $M>1.5$, the increase in corridor width (above no-wind case) due to tail wind is approximately equal to the decrease due to head wind. For stronger winds at the same Mach number,

head winds produce progressively higher decrease in corridor width than the increase due to tail winds. The largest variations in corridor widths due to tail winds occur for $M < 1.3$.

(4) The effect of winds on sonic boom corridor is more pronounced for flights above the tropopause where isothermal conditions prevail, but is less significant for flights below the tropopause where temperature effects are dominant. Based on the results for non-standard atmospheres, the ground temperature is the greatest single meteorological parameter affecting the sonic boom corridor; the influence of ground temperature is such that higher than standard temperature constricts it, while lower than standard temperature expands it.

In a previous investigation Kane and Palmer (see capsule summary P-42) obtained results concering the lateral spread of sonic booms which were more realistic than those of the present paper because they used representative wind profiles. The results of the present paper for high altitudes and high winds are somewhat unrealistic because the winds do not normally blow as hard as assumed above 40,000 feet.

P-133

TIME DEPENDENCE OF VARIANCES OF SONIC BOOM WAVEFORM

G. Kamali, A. D. Pierce

Nature, Vol. 234, Nov. 5, 1971, pp. 30-31

An analysis of certain data obtained during the Edwards Air Force Base sonic boom experiments of 1966 is presented in this paper. The sonic boom pressure signatures considered here were recorded at forty-two ground level microphones, equally spaced in an 8000 foot linear array, during level overflights of F-104 fighter aircraft at flight Mach numbers of approximately 1.3 and at an altitude of approximately 30,000 feet. The array was almost directly beneath the flight path. The variations in the signatures recorded by different microphones during the same overflight were believed to be caused primarily by atmospheric turbulence. The purpose of this investigation was to analyze these variations and to determine the extent to which the analysis substantiates Crow's theory concerning turbulent scattering of shock waves. For details of this theory the reader should refer to capsule summary P-79. The present analysis is concerned mainly with the ensemble average of the square of the ratio $(P^s)/\Delta P_o$:

$$\psi^2(t) = (t/t_c)^{-7/6} = \left\{(P^s)/\Delta P_o\right\}$$

where (P^s) is the scattered wave, minus a phase shift term which represents the increment that may be added to the incident wave to account (to first order) for the change in time of onset caused by transit speed fluctuations. The quantity ΔP_o is the overpressure of the incident step pulse. The parameter t_c is a complex function of (height dependent) parameters characterizing the atmosphere's state of turbulence in the inertial subrange and t is time.

The mean waveform $\{P\}$ and variance $\left\{\left[P-\{P\}\right]^2\right\}$ are estimated in the present paper from a computation of the numerical averages of $P_i(t)$ and $\left(P_i(t) - P_{ave}(t)\right)^2$ for the set of sample signatures. The relative variance $\{\psi^2(t)\}$ is defined as

$$\{\psi^2(t)\} = \left\{\left[P-\{P\}\right]^2/(\Delta P_o)^2\right\}$$

where ΔP_o is the peak overpressure of the average waveform.

A comparison of the results of the present paper with the results predicted by Crow's theory is made based on data for two different flights 30 seconds apart. For times between about 7 and 27 ms the slopes of the experimentally determined curves of relative variance versus time agree quite well with that predicted by Crow's theory. It is pointed out that this time region includes nearly all portions of the waveform except the front and rear shocks, for which Crow's theory is least accurate. Thus, it is concluded by the authors that these results provide substantial support for Crow's theory.

P-134

REAL-GAS EFFECTS IN VERY WEAK SHOCK WAVES IN THE ATMOSPHERE AND THE STRUCTURE OF SONIC BANGS

J. P. Hodgson and N. H. Johannesen

J. Fluid Mechanics, Vol. 50, Part 1, November 15, 1971, pp. 17-20

Starting from the conservation equations of mass, momentum, and energy, and using the rate equation for relaxation of vibrational energy, an approximate expression is derived for the thickness of weak fully dispersed shock waves. This expression, together with available data on the thermodynamic properties of air, is used to show that shocks of the strength expected in sonic booms are fully dispersed. Estimated relaxation times for dry and humid air lead to wide variations in possible thickness, varying from millimeters to meters.

In a later paper (see capsule summary P-172) Hodgson performs a similar analysis which takes into account the vibrational relaxation effects of both oxygen and nitrogen in contrast to the present paper which considers only oxygen. A more extensive discussion of the effects of atmospheric pressure, temperature and humidity is also presented in the later paper.

P-135

THE PENDLETON PROJECT--A STUDY OF THE ATMOSPHERIC EFFECT ON WEAK SHOCK WAVES TRAVERSING LONG RAY PATHS

G. A. Herbert, W. A. Hass

NOAA Technical Report ERL 220-ARL 1, Dec. 1971

This project, conducted between September 1968 and May 1970, was designed to study in detail

the effects of meteorological conditions on sonic booms. Data consisted of booms resulting from U.S. Air Force SR-71 training missions flying at or above 20 km and faster than Mach 2.5. These were recorded by a dense grid and line array of self-activated microphone-recorder systems. Meteorological data consisted of conventional upper-air soundings to above aircraft level, and routine, detailed sampling of boundary layer structure and turbulence by means of a specially instrumented light aircraft.

Observed overpressures and those computed using the Hayes' computer program (see capsule summary P-98) were quite consistent, and it was found that the effects of the real, gross atmosphere were within 5% of those of a standard atmosphere with no wind. The excellent correlation between observed and computed overpressures, moreover, remained unchanged with lateral offset of the flight track, indicating that the program model is correctly taking propagation aspects into account. The program, however, overestimated the magnitude of the signature pressures in comparison with those observed. It is hypothesized that this may be due to errors in the wave-shaping portion of the program, to system calibration errors, to variations in the response characteristics of the microphones, or to a combination of these factors.

The lack of overflights during the summer when strongly turbulent boundary layer conditions are most common, and the general degradation of signature detail due possibly to system frequency response as well as to interpretation, made it difficult to test the various scattering models. Nevertheless, it is concluded that the limited data tend to support Crow's (see capsule summary P-79) concept relating a "critical time," effectively a measure of turbulence, to the observed variability in observed overpressures.

A previous verification of the validity of the Hayes' computer program was made by Haefeli for both steady, level flight and maneuvering flight (see capsule summary P-97). The present investigation dealt only with steady level flight, but a much larger amount of experimental data was used than was used by Haefeli.

Herbert, Hass, and Angell also made an investigation of atmospheric effects on sonic booms during the sonic boom experiments at Edwards Air Force Base (see capsule summary P-103). That investigation concentrated much more heavily on the effects of atmospheric turbulence than did the present investigation.

P-136
ANALYSIS OF THE MULTIPLE SCATTERING OF SHOCK WAVES BY A TURBULENT ATMOSPHERE
W. J. Cole and M. B. Friedman
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 67-74

In this paper it is shown that shock thickening can be derived within the framework of a nonperturbative multiple-scattering theory. This theory provides for a direct evaluation of the fluctuation intensity. The procedure inherently incorporates the coupling between the intensity of the fluctuations and the continuously thickened shock profile.

The analysis is based upon the method of "smoothing," which involves the separation of the solution field into its coherent and incoherent (fluctuating) parts. The first-order "smoothing" approximation is equivalent to assuming that the principal contribution to the fluctuations is the single scattering of the coherent field instead of the incident undistorted field, as assumed by Crow (see capsule P-79). A comparison of the approximate solution obtained using the "smoothing" method and an "exact" numerical method showed the smoothing method predicts accurately the behavior of high frequencies, whereas the single-scattering approximation of the type developed by Crow develops inaccuracies at high frequencies.

To apply this scattering theory to the sonic boom problem, it is assumed that the turbulence that distorts the sonic boom N-wave is concentrated in the 3000-ft. boundary layer near the ground. It is further assumed that the shock front is essentially planar and that the scattering experienced by the shock is associated with the sharp pressure rise across the shock and is insensitive to the rate of expansion behind the shock so that only a step function shock need be considered. Therefore, the problem dealt with is that of a plane shock incident on a random half space with uniform statistical properties. The procedure results in a Burgers' equation similar to that found by George and Plotkin (see capsule summary P-124), which is solved to get an expression for the coherent acoustic fluid density.

In the determination of the incoherent field the phase-shift contribution (which is not measured in practice) and the actual measured fluctuation contribution are separated. This makes it possible to obtain accurate estimates of actual measured shock thickening and fluctuation intensities. Plotkin and George (see capsule summary P-124) developed a method of calculating an upper bound on the fluctuation intensity, but not the actual value of the intensity. Their method is equivalent to assuming that the observed fluctuations are caused by scattering from the final thickened profile, instead of the actual continuously thickened profile, as assumed in the present paper. The analysis of the present paper predicts values for the fluctuation intensity that are an order of magnitude smaller than those predicted by George and Plotkin for a given set of turbulence parameters.

P-137
PRELIMINARY INVESTIGATION OF SONIC BOOM WAVE FORMS NEAR FOCUSING RAY SYSTEMS
Sanford S. Davis
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 133-146

An investigation is presented in this paper of the characteristics of cusped shock waves by using the analogy between steady supersonic flows and unsteady two-dimensional flows. In this analogy a thin wing is used to induce a cusped shock wave in the flow field.

A fundamental difficulty with the linearized, analytical approach to the cusping problem is that the solution satisfies the mixed Tricomi equation. This difficulty is bypassed in the wing problem because the solution can be expressed directly as an integral over a distribution of elementary sources on the wing planform. Furthermore, it is shown that the behavior of the singularities of this linear solution at and near the cusp can be inferred directly by the confluence of the three neighboring roots corresponding to the intersection of the leading edge of the wing and the trace of the Mach forecone, from the field point (x,y,z).

It is proposed that the form of the linearized solution derived here, when expressed in a geometrical acoustics coordinate system, can be used in conjunction with Whitham's hypothesis to obtain a uniformly valid first approximation to the exact nonlinear disturbance field. shock. It is shown that in these two-dimensional cases, significant errors result when waves are incident on the shock rather obliquely.

The singularity occurring at the intersection of a conical flow field and a shock is shown to be cancelled by reflected waves from the shock for finite Mach number shocks. However, the higher order terms necessary to determine the behavior at this point were not found by the technique used here.

The propagation of waves through a nonuniform region before reaching a shock is shown to affect the strength of the waves and, therefore, the strength of the shock after its intersection with the wave. Regions of two-dimensional flow bounded by a shock and three-dimensional waves are shown to be eliminated as the three-dimensional waves propagate across the region.

It is pointed out that all of these effects can be expected to produce significant variations in near-field shock strengths.

An experimental phase is proposed which would use a wing with a concave leading edge, inboard subsonic and outboard supersonic, to induce a steady-state cusped shock wave in the disturbed region below the wing. A static pressure rake would then be used to measure the shock wave signature in this steady-flow analogy to the sonic cutoff problem. The author concludes that the results of such an experimental investigation into this wing-induced cusping phenomenon should serve as an ideal "first cut" for the variation in strength of a shock wave near a caustic.

P-138

THE EFFECTS OF ATMOSPHERIC INHOMOGENEITIES ON SONIC BOOM

A. R. George

NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 33-57

This paper presents a review of the theories which have been derived to explain the manner in which atmospheric irregularities distort sonic boom signatures. The theories discussed are those of Pierce (see capsule summary P-80), Crow (see capsule summary P-79), George and Plotkin (see capsule summary P-124), and others.

Bringing the different aspects of the various theories together results in the following physical picture of the effects of inhomogeneities on sonic boom propagation:

(1) Only the largest scale atmospheric inhomogeneities can result in overall geometric focusing and defocusing of N-waves.

(2) Somewhat smaller scale inhomogeneities can focus and defocus the higher frequency components of the wave (parts near the shock), but diffraction makes lower frequency scattered waves appear as random perturbations about the N-wave shape. The lowest frequencies are only weakly affected and propagate essentially unchanged.

(3) The energy lost in the scattered waves results in a decay in amplitude of the high-frequency components of the signature that is eventually balanced by nonlinear steepening effects. As the signature loses its high-frequency components, geometric focusing becomes less important.

(4) As the diffraction parameter increases with propagation distance or wavelength there is a progressive shift from geometric focusing to diffraction-dominated random perturbations and shock thickening.

(5) Because of the decay of the high-frequency components of the original wave, the maximum nondimensional random perturbation can be only of order 1. These perturbations will have frequencies of the order of the maximum frequencies left in the signature.

(6) Precise predictions are still not possible because of both lack of knowledge of atmospheric structure and some approximations in the available analyses. However, approximate predictions based on estimated atmospheric structures should be possible with some further development.

In another paper written at about the same time the present one was written, Pierce and Maglieri (see capsule summary P-154) presented a similar review of the theories concerning atmospheric effects on sonic booms. The basic difference between the two papers is that in discussing the large rise times of sonic boom pressure signatures, Pierce favors his wavefront-folding mechanism, while George favors his balancing of acoustic scattering of high frequencies and nonlinear effects (see capsule summary P-124).

P-139

THE ACCURACY OF THE LANDAU-WHITHAM SHOCK STRENGTH RULE IN SOME NEAR FIELD SITUATIONS

A. R. George and W. F. Van Moorhem

NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 373-384

Several important effects in the near field for sonic boom problems are discussed in this paper. These effects involve the interaction of a plane shock with two-dimensional weak waves of the progressing type. The straightforward application of the one-dimensional Landau-Whitham theory for determining shock strength would just add the pressure change of the perturbation to the pressure jump across the shock. It is shown that in these two-dimensional cases, significant errors result when waves are incident on the shock rather obliquely.

The singularity occurring at the intersection of a conical flow field and a shock is shown to be cancelled by reflected waves from the shock for finite Mach number shocks. However, the higher order terms necessary to determine the behavior at this point were not found by the technique used here.

The propagation of waves through a nonuniform region before reaching a shock is shown to affect the strength of the waves and, therefore, the strength of the shock after its intersection with the wave. Regions of two-dimensional flow bounded by a shock and three-dimensional waves are shown to be eliminated as the three-dimensional waves propagate across the region.

It is pointed out that all of these effects can be expected to produce significant variations in near-field shock strengths.

P-140
THEORETICAL PROBLEMS RELATED TO SONIC BOOM
W. D. Hayes, J. H. Gardner, D. A. Caughey, and F. S. Weiskopf, Jr.
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 27-31.

This paper is a brief report of research that was in progress at Princeton University on problems of wave propagation and sonic boom at the time this conference was held. The following four topics are discussed:

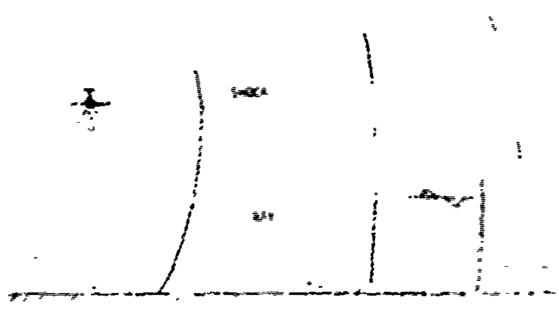
(1) computation of transonic flows with shock waves;
(2) singular rays;
(3) bangless boom optimums; and
(4) general wave theory.

The passage of a sonic boom through a caustic is governed by equations that are essentially the same as the classical ones of transonic flow. Thus the investigation of transonic flows with shock waves could shed light on this problem. The problem taken up was that of a symmetrical airfoil in transonic flow, with the flow subsonic at infinity. No results had yet been obtained.
A singular ray is a ray in geometric acoustics at which the solution is singular, so that the solution of geometric acoustics fails in its neighborhood. The particular aspect of singular ray problems discussed here is the influence of nonlinear terms on their solution. Two canonical problems are distinguished. One is the singular ray as a singular direction for the F-function for a finite body. The other is the singular ray in a conical flow from a semi-infinite body. In the first case it is concluded that the shock wave present absorbs the singular ray in such a way that the lateral gradients in the remaining wave system are negligible. In the conical case it is concluded that the problem can probably only be solved numerically.

The discussion of bangless boom optimums deals with sonic boom minimization and is discussed in another capsule summary (see capsule summary M-49). The discussion of work proceeding in the area of general wave theory is very brief, as no results had yet been obtained.

P-141
VARIABILITY OF SONIC BOOM SIGNATURES WITH EMPHASIS ON THE EXTREMITIES OF THE GROUND EXPOSURE PATTERNS
Harvey H. Hubbard, Domenic J. Maglieri, and Vera Huckel
NASA SP-255 Third Conference on Sonic Boom Research, 1971, pp. 351-359.

An investigation into the characteristics of sonic boom pressure signatures near the region of lateral cutoff is presented in this paper. Pertinent published measurement results are reviewed, and the results of an experiment performed to better define the physical phenomena involved are described. In this experiment an F-104 made six flights at M = 1.5 at an altitude of 37,200 feet, and numerous other flights at M ≈ 1.3 at an altitude of 33,700 feet. For the first set of flights, data were obtained at various lateral distances out to a distance of approximately twice the predicted cutoff distance with microphones spaced about one mile apart. The purpose of the second set of flights was to evaluate overpressure patterns in the region of the caustic formed at the lateral cutoff location. Measurements were made with the use of special microphone arrays, the measuring stations being about 200 feet apart. The setup is shown in the figure below, which was taken from this paper. The figure shows a 3200 ft horizontal and a 150 ft vertical array. The flights were made so that the edge of the exposure pattern was placed in or near this array.



Experimental Setup Used to Investigate Lateral Cutoff

The following conclusions were arrived at as a result of the review of previous measurements and as a result of the experiments described above:

(1) The overpressures generally decrease and rise times generally increase as lateral distance from the ground track increases.

(2) Overpressure variability is greater at locations 10 to 13 miles laterally from the ground track than for locations on the track for a range of Mach numbers and altitudes.

(3) The maximum measured overpressure values at 10 to 13 miles off the track for a range of altitudes and Mach numbers are of the same order of magnitude as those measured on the track.

(4) Near lateral cutoff there is a general decrease in overpressure as distance increases rather than a sharp drop. There is also a corresponding trend from N-shape signatures, which are observed as booms, to signatures with no definite shape characteristics, which are observed as acoustic rumbles.

(5) Although signatures representative of caustic conditions were observed near the edge of the pattern, there was no evidence of substantial overpressure enhancement.

This is an excellent summary of the state of knowledge concerning sonic boom characteristics in the region of lateral cutoff.

P-142
UNIFORM WAVEFRONT EXPANSIONS FOR DIFFRACTED AND FOCUSING WAVES
M. K. Myers
NASA SP-255, Third Conference on Sonic Boom Research, Oct. 29-30, 1971, pp. 75-86

The purpose of the research discussed in this paper is to develop theoretical descriptions of the propagation of shock waves in problems involving diffracted wave systems and problems involving focusing of waves. In each case the dominant feature is the existence of a singularity in the surface forming the wavefront of the disturbance field calculated from a linearized theory. For problems involving diffraction, the wave surface is formed by two or more segments tangent to one another along curves analogous to shadow boundaries in optical diffraction problems. In the focusing case, the wavefront is cusped, and the surface traced by the cusp on the wavefront is a caustic of the associated system of rays.

The fundamental objective of determination of shock waves in these problems is approached in two separate stages. The first stage, which underlies the entire study, consists of determining satisfactory approximations to the linearized solution of problems of interest, especially in the vicinity of the linear wavefronts. The linear solutions are easily written in exact form as integral expressions, but these are generally too complex to be useful in practice. The approach of the present paper is to seek asymptotic approximations to the linear solutions valid near the wavefront appropriate to the problem being studied. The approximation sought is one free of anomalous singularities that arise as a result of the process of approximation and that generally exist neither in the full linear solution nor in the exact solution to the problem.

The second stage of the study is to develop methods, analogous to that of Whitham (see capsule summary G-3), that correct the linearized solution by means of a straining of coordinates to yield a first approximation to the exact solution of the problem. This paper treats only the first, or linear, stage of the work.

Asymptotic expressions for the linearized velocity potential are derived for: (1) single waves systems, such as plane flow past a symmetrical airfoil, flow past a body of revolution, and steady flow past a symmetric nonlifting wing with a smooth leading edge; (2) diffracted wave systems, such as the steady flow past a nonlifting wing with a supersonic leading edge having discontinuities in spanwise slope and steady flow past a rectangular wing of constant cross section; and (3) a focusing wave system resulting from a steady flow past a nonlifting wing of constant cross section with a leading edge concave to the stream direction.

Before the validity of the expressions derived here can be established experimentally, the second stage of the development of the theory must be completed, i.e. the linearized solution must be corrected by means of a straining of coordinates to yield a first approximation to the exact solution to the problem.

P-143
SOME ATTEMPTS TO THEORIZE ABOUT THE ANOMALOUS RISE TIMES OF SONIC BOOMS
Allan D. Pierce
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 147-160

This paper is a condensation of a portion of an earlier paper by Pierce and Maglieri (see capsule summary P-154). The theories of Crow (see capsule summary P-79), George and Plotkin (see capsule summary P-124), and Pierce (see capsule summary P-123) are summarized and compared. The reader is referred to capsule summary P-154 for further details of this work.

P-144
PERTURBATIONS BEHIND THICKENED SHOCK WAVES
Kenneth J. Plotkin
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 59-66

The theories developed by Crow (see capsule summary P-79) and George and Plotkin (see capsule summary P-124), which deal with first order acoustic scattering of shock waves and weak shock wave structure in a turbulent medium, respectively, are used in this paper to calculate the perturbations behind a steady thickened shock. The calculation is based upon the decay of first order scattered waves through further scattering. A number of approximations were employed, the most serious being that the question of distinctness of the multiply scattered waves

was not considered. It was felt, however, that the present calculation provided a reasonably good estimate of the physical situation.

It is shown that the perturbations depend on the factor $\epsilon^{2/3}L_o$, while the shock thickness depends upon the factor $\epsilon^2 L_o$ where ϵ^2 is the turbulent intensity and L_o is the turbulent macroscale length. Shock thickness and the perturbations thus depend upon the turbulent parameters in different ways. The moderate variations with turbulent intensity of the maximum perturbations behind the shock found here are stated to be consistent with much previous experimental data.

Since the shock thickness depends upon the factor $\epsilon^2 L_o$, it is pointed out that measurement of shock thickness should provide a good indication of the intensity of the turbulence if L_o is known. It is also pointed out that, since the envelopes of the perturbations were shown to depend upon $\epsilon^{2/3}L_o$, they reflect mainly the scale of the turbulence. It is concluded that with further refinements of this theory, it is possible that the measurement of perturbations and shock thicknesses may be a useful diagnostic technique in the determination of the form of atmospheric turbulence.

This is an excellent paper which not only gives clear, concise summaries of the theories of Crow, and George and Plotkin, but also illustrates the application of these theories to a specific problem.

P-145
NONLINEAR ACOUSTIC BEHAVIOR AT A CAUSTIC
R. Seebass
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 87-120

The purpose of this paper is to modify basic sonic boom theory to include nonlinear effects not properly accounted for in the neighborhood of a caustic. The basic theory accounts for nonlinear effects on the propagation of the pressure signal down a ray tube (see capsule summary P-98), but the concept of ray tubes is a linear one. In regions where the differential ray tube area becomes small, the pressure becomes correspondingly large and the concept of a ray tube fails. The envelope of the rays is a caustic surface; this surface is the locus of cusps in the acoustic wavefronts.

The mathematical formulation of the behavior of the pressure signature near a caustic was given by Hayes (see capsule summary P-91). The present paper is concerned with the detailed structure of the wavefront as it reflects at a caustic surface, where nonlinearity is an essential part of the problem.

An aerodynamic problem equivalent to the behavior at a caustic is introduced. The problem considered is a steady flow of uniform speed U and varying free stream sound speed $a_o(y)$ past a slender airfoil. A coordinate system (x,y) is introduced such that x is in the direction of flow and it is required that $a_o(0) = U$. The initial flow is taken to be at constant pressure with a nonuniform entropy distribution. A simple transformation is applied to the nonlinear potential equation which governs this problem resulting in a description of the nonlinear acoustic behavior at a caustic in terms of a linear equation. Using this result an analytical solution is written, in implicit form, for a special incoming signal with finite rise time. This solution is then studied by numerical evaluation and graphical presentation with a digital computer.

P-146
FINITE DIFFERENCE CALCULATION OF THE BEHAVIOR OF A DISCONTINUOUS SIGNAL NEAR A CAUSTIC
R. Seebass, E. M. Murman, and J. A. Krupp
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 361-371.

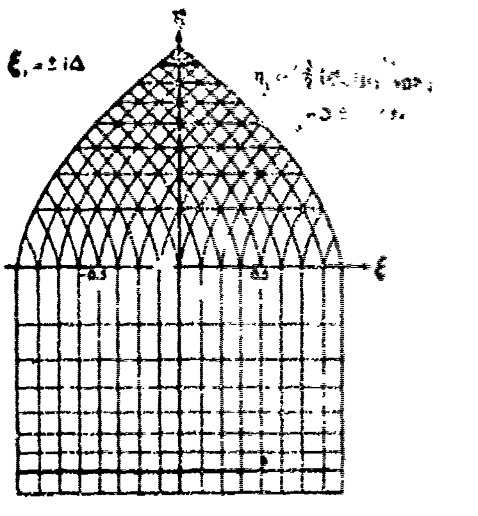
This paper presents a numerical technique for predicting sonic boom pressure signatures in the vicinity of a caustic. The essential problem lies in the solution of the following nonlinear equation:

$$(\eta + \psi_\xi)\psi_{\xi\xi} - \psi_{\eta\eta} = 0$$

The solution to this equation in a domain D, consisting of two characteristics arcs $\xi \pm 1 = \pm 2/3\eta'^{3/2}$ for $\eta > 0$, and the lines $|\xi| = 1$ and $\eta = -(3/2)^{2/3}$ for $\eta < 0$ (see figure below, which was taken from this paper) is obtained by solving a boundary value problem with boundary data determined by the solution to the linear Tricomi equation,

$$\eta\psi_{\xi\xi} - \psi_{\eta\eta} = 0$$

in D. A numerical solution is effected by dividing the ξ axis of D into 2N equal intervals of length Δ and the η axis into the intervals determined by the family of linear characteristics emanating from the mesh points $\xi_i = i\Delta$, $i = 0, \pm 1, \ldots, \pm N$. The difference equation for the nonlinear equation above is then obtained using a first-order implicit scheme when the equation is hyperbolic and a second-order [illegible] scheme when it is elliptic. Several [illegible] examples are then given.



Domain of Solution and Mesh Spacing

[illegible] out by the authors, the difference [illegible] presented here needs further refinement [illegible] will give satisfactory results.

[illegible]

[illegible] BOOM RESEARCH IN GERMANY

[illegible]

[illegible], Third Conference on Sonic Boom Research, [illegible] 429-436

[illegible] of this paper describes a closed form [illegible] for the sonic boom in a polytropic atmos- [illegible]. This solution was also presented in a later [illegible] capsule summary P-158). The reader is [illegible] to the capsule summary of that paper for [illegible].

[illegible]

[illegible] WIND-TUNNEL SONIC-BOOM SIGNATURES [illegible] A WHITHAM F-FUNCTION

[illegible] Thomas

[illegible], Third Conference on Sonic Boom Research, [illegible]-217

[illegible] describes a method of extrapolating [illegible] pressure signatures without the use [illegible] in F-function. The method used is the same [illegible] described in capsule summary P-1[illegible]. The [illegible] referred to that capsule summary for [illegible].

[illegible]

[illegible] DIFFRACTION OF A PULSE BY A THREE- [illegible]

[illegible] and Fanny [illegible]

[illegible], Third Conference on Sonic Boom Research, [illegible]-180

[illegible] solution for the diffraction of a plane [illegible] pulse by a three-dimensional corner of a [illegible] outlined in this paper. The solution is [illegible] by separation of variables. The detailed [illegible], the eigenvalues, and eigenfunctions are [illegible] in the paper summarized in capsule summary [illegible].

[illegible] of mean value theorems derived in [illegible] paper are presented in the present paper. [illegible] theorems were derived for solutions of wave equations so that the resultant value at the vertex of a cone could be related to the incident wave or the value at the vertex of a different cone. These theorems are shown to be useful in extending the knowledge of the conical solutions to the adjacent corners or edges. The case of a plane wave incident on a three-dimensional corner is also discussed.

The reader is referred to capsule summary P-125 for further details of this work.

P-15[illegible]

THE EFFECT OF ATMOSPHERIC INHOMOGENEITIES ON THE SONIC BOOM

Kenneth J. Plotkin

Ph.D. Thesis, Cornell University, 1971

An investigation into the effect of atmospheric inhomogeneities on the sonic boom and other weak waves is presented in this thesis. First, the propagation of sonic booms through a quiescent, smoothly varying atmosphere is examined. Geometric acoustics (see capsule summary P-8) is used to extend the linearized flow (acoustic) solution from near the aircraft to distances far enough away so that atmospheric variations must be taken into account. The equations of geometric acoustics are derived, and ray paths are calculated for a horizontally stratified atmosphere. This acoustic solution is then corrected by the inclusion of lowest order nonlinear wave steepening, which gives the classical N-wave signature in the far field. A simplified method for calculating signatures at the ground directly under the flight track, without the need for a computer for each case, is presented.

The limitations involved in neglecting the effects of atmospheric turbulence are discussed in some detail. It is shown that geometric acoustics cannot account for the fact that sonic boom shock waves are on the order of 10^3 times as thick as predicted, or for the random perturbations which appear behind the shocks.

The thickening and pertubations are due to the interaction of shock waves with turbulence, so the case of a plane shock passing through turbulence is examined using scattering theory. This theory is an expansion scheme in which ϵ, the strength of the turbulence, is the expansion parameter. The physical picture developed is that high frequency components of the shock wave are scattered out of the shock's propagation direction, causing the shock to thicken. These components fall behind and appear as the perturbations following the shock.

The waves scattered out of the shock are first order in ϵ. They carry energy of order ϵ^2, so that the change to the shock is a dissipation of order ϵ^2. This is therefore a second order scattering effect, and second order scattering must be investigated to see if this dissipation is the only effect of order ϵ^2. It is found that for shock thickness small compared to the turbulent macroscale length other effects are small, so that the order ϵ^2 change to the shock shape can be found by accounting for the energy in the first scattered waves.

The pertubations behind the shock are investigated, based on a first order scattering analysis by Crow (see capsule summary P-79). It is found that first scattering is inadequate to describe the pertubations behind a steady shock in unbounded turbulence. Crow's analysis is modified to allow for the decay of first scattered waves by multiple scattering. An approximate method is used to estimate this decay in order to simplify the calculations. Root mean square perturbations behind the shock are calculated and are found to be in good agreement with the observed order of measured perturbations.

The theory developed in this thesis is also described in a paper by George and Plotkin (see capsule summary P-124).

P-151

EXTRAPOLATION OF SONIC BOOM PRESSURE SIGNATURES BY THE WAVEFORM PARAMETER METHOD

C. L. Thomas

NASA Tech. Note, NASA TN D-6832, June, 1972

A method of extrapolating sonic boom pressure signatures based upon the use of three parameters to describe the waveform is presented in this paper. In the approach used here, the wave-

form is approximated by an arbitrary number of linear segments. For each segment the waveform parameters m_i, ΔP_i, and λ_i are defined as follows: m_i is the slope $\partial P/\partial t$ of segment i, which may be positive or negative (here t is the time associated with a waveform point); ΔP_i is the pressure rise across the shock at [illegible] of segments i and i-1. Often there will be no shock at the juncture, in which case ΔP_i is zero. Finally, λ_i is the time duration Δt of segment i.

Using the principle of conservation of the Blokhintsev energy invariant along ray tubes, and accounting for nonlinear distortion of the waveform by assuming that the propagation speed of a point on a pressure wave is equal to the value of u + a for the point (here a is the sound speed and u is the fluid particle speed due to wave passage), differential equations are derived for the rate of change with time (as seen by an observer moving down the ray tube with the wave) of m_i, ΔP_i, and λ_i. These equations are then integrated to get expressions which can be used in a stepwise fashion to calculate the waveform at any given point if the waveform near the aircraft is known.

This method is shown to be equivalent to the F-function method used by Hayes, et al. (see capsule summary P-98). However, it is suggested by the author that the waveform parameter method may provide a more suitable approach for automatic computation because the necessity of using the area-balancing technique for locating shocks (see capsule summary G-3) is eliminated.

A computer program based upon the waveform parameter method is presented and discussed, and a sample case demonstrating program input and output is given.

In a previous paper (see capsule summary P-148) Thomas proposed the use of this method for extrapolating wind tunnel pressure signatures.

P-152
EFFECT OF SST OPERATIONAL MANEUVERS ON SONIC BOOM
G. T. Haglund, E. J. Kane
AIAA Paper No. 72-196, Jan. 17-19, 1972

This paper is essentially the same as the one described in capsule summary P-157. The reader is referred to that capsule summary for details of this work.

P-153
SONIC BOOM PROPAGATION THROUGH A STRATIFIED ATMOSPHERE
W. D. Hayes, H. L. Runyan, Jr.
Acoustical Society of America, Second Sonic Boom Symposium, Nov. 3-6, 1970 (The Journal of the Acoustical Society of America, Vol. 51, No. 2 (Part 3) February 1972, pp. 695-701)

A summary of the theory underlying the Hayes, Haefeli, Kulsrud computer program (see capsule summary P-98) is presented in this paper. This computer program calculates the sonic boom signature due to a maneuvering aircraft in a horizontally stratified atmosphere. The reader is referred to capsule summary P-98 for a discussion of this theory.

The summary presented in this paper is very clear and concise. For the reader who desires an overall idea of the theory underlying the Hayes computer program without becoming involved in the [illegible] mathematics, the present paper is well [illegible].

P-154
EFFECTS OF ATMOSPHERIC IRREGULARITIES ON SONIC BOOM PROPAGATION
Allan D. Pierce and Domenic J. Maglieri
Acoustical Society of America, Second Sonic Boom Symposium, Nov. 3-6, 1970 (The Journal of the Acoustical Society of America, Vol. 51, No. 2 (Part 3) February 1972, pp. 702-721)

A review is given in this paper of the theories developed and experimental results obtained concerning the effects of atmospheric irregularities on sonic boom propagation. These effects include the observed random variations in boom overpressures from those expected for a stratified atmosphere, the anomalously large and variable rise times, and the occurrence of spiked or rounded waveforms rather than the characteristic N waves. The extent of variability in data recorded during actual flight tests is summarized in the form of histograms, representing experimentally obtained probability density functions. Most of this data was taken from an earlier paper by Garrick and Maglieri; the reader is referred to capsule summary P-81, which summarizes that paper, for further details.

The physical mechanisms believed to be responsible for the variations and anomalous features in the signatures are described by summarizing and comparing the various theories that have been developed to explain these phenomena. These theories include those of Crow (see capsule summary P-79), George and Plotkin (see capsule summary P-124), Pierce (see capsule summaries P-80 and P-123), Horning (see capsule summary P-131), and others.

After analyzing and comparing each of the above theories and taking into account the experimental data, the following conclusions are reached:

(1) There appears to be little widespread agreement on the details of sonic boom distortion by atmospheric turbulence. The phenomena of refraction, focusing, and diffraction each appear to be an integral part of the distortion process. These effects have all apparently been observed, either in field tests or in laboratory experiments. The concept of wavefront folding may be useful in explaining the anomalous rise times, but the experimental confirmation that such folding takes place is still lacking. The established mathematical techniques for analyzing the distortion appear to be those of first order scattering and of multiple scattering.

(2) Although the theoretical development is in a state of flux, there is some suggestion that the one meteorological parameter which best summarizes the atmosphere's gross state of turbulence, insofar as sonic boom distortion is concerned, may be Crow's characteristic time t_c. An experimental check is still lacking for the general prediction that t_c governs waveform variability.

George wrote a paper at about the same time the present one was written (see capsule summary P-138) in which he presented a similar review of the existing theories concerning atmospheric effects on sonic booms. The basic difference between the

two papers is that Pierce favors his wavefront-folding mechanism for explaining the large rise times of sonic boom pressure signatures, while George favors his balancing of acoustic scattering of high frequencies and nonlinear effects (see capsule summary P-124).

P-155
THEORETICAL AND EXPERIMENTAL STUDIES OF THE FOCUS OF SONIC BOOMS
Jean-Claude L. Wanner, Jacques Vallee, Claude Vivier, Claude Thery
The Journal of the Acoustical Society of America, Vol. 52, No. 1 (Part 1), 1972, pp. 13-32

In this paper the results of a theoretical and experimental study concerning the focus of sonic booms are presented. The theoretical studies were made by ONERA and by Institut Franco Allemand de St. Louis (France) and the experimental investigations by the Flight Test Center of Istres and by the Service Technique Aeronautique.

The theoretical studies helped identify the different cases of focus (linear acceleration, turn, pushover) and superfocus (entry to turn). They also showed that it was possible to guide an airplane in order to produce focusing in a measurement zone of realistic size after measurement of the actual characteristics of the atmosphere.

In the experimental investigation, flights of Mirage III and Mirage IV supersonic aircraft were made as part of the following four exercises: (1) Jericho-Instrumentation--test and choice of the different types of sensors; (2) Jericho-Focalization--focus due to acceleration at low altitude (2000 feet); (3) Jericho-Virage--focus due to turn and acceleration at high altitude (36,000 feet); and (4) Jericho-Carton--effects of variations of acceleration and lateral spread on the focus factor and investigations of the "super-focus." An array of ground microphones was used to determine the pressure patterns resulting from the various aircraft maneuvers.

The following are the most significant conclusions reached as a result of these tests:

1. The boom intensity is multiplied by 5 in the case of a focus and by at least 9 for a superfocus.

2. The superfocus occurs over an area of approximately 300-ft radius, and the region of focus is a "line" 300 feet wide. These zones are located at a lateral distance of about ten miles from the flight path. These locations can be modified substantially by atmospheric effects.

In another investigation (see capsule summary P-162) Haglund and Kane obtained results that confirm and complement those of the present investigation. That investigation dealt with the caustics produced by steady flight near the threshold Mach number, caustics produced by longitudinal accelerations, sonic boom characteristics near lateral cutoff, and the vertical extent of shock waves attached to near sonic (M=1.0) airplanes. Haglund and Kane found that pressures at caustics produced by longitudinal accelerations beginning from Mach 0.95 ranged from 2 to 5 times those which would be observed during steady, level flight at about Mach 1.2. This compares with the corresponding factor of 5 found in the present investigation.

This is a very significant paper in that the overpressures at caustics cannot yet be accurately predicted due to nonlinear effects. The measured data obtained in this investigation concerning the overpressures at a focus or superfocus were a significant contribution to sonic boom knowledge.

P-156
PROPAGATION OF A WEAK SHOCK WAVE THROUGH A TURBULENT MEDIUM
S. M. Phinney, L. S. Taylor
Naval Ordnance Laboratory, NOL TR 72-130, May 31, 1972

The propagation of a weak nearly planar shock wave through a slightly inhomogeneous medium is studied in this paper. The method used by Whitham in an earlier paper (see capsule summary P-14) is used here also. This method uses the characteristic differential equation for infinitesimal waves together with the shock relations in order to obtain a single determinate system for the dependent variables. The essence of the system is that the weak wave system that is reflected back from the shock is ignored.

Whitham's method is generalized to include upstream disturbances of density and velocity. These disturbances are small enough so that a plane wave will remain nearly plane. The equations for a finite strength shock wave are used as a starting point so that the cumulative effect of second order terms will not be lost.

The following method is used: First, the characteristic equation for wave propagation and the shock relations are expressed in a moving coordinate system that appears to reduce the velocity in front of the shock to zero so that the equations used by Whitham apply. A wave front function, α, is introduced by which shock velocity and position are defined. An identity connecting the wave function, α, and the ray tube area allows the characteristic equation to be put in terms of α, as well as variations in pressure in front of the shock and sound speed that are interpreted as forcing functions. Finally, the equation is transformed back to fixed coordinates to put it in a useful form. This transformation makes the turbulent velocity appear as another forcing function.

The results show that, in the limit of infinitesimally weak waves and weak upstream turbulence, the ray optic solutions are recovered, as expected. The higher approximations that result from the present method give the modifications to the ray optic solutions. Each successively higher approximation involves a solution to linear equations which have the previous approximations as forcing functions. For cases in which the upstream turbulence is given in terms of its statistical characteristics, the results show that it is possible to find the corresponding statistical description of the shock wave motion.

The most well known theories concerning the effects of atmospheric turbulence on the propagation of weak shock waves are those of Crow (see capsule summary P-79) and Pierce (see capsule summary P-80). Their basic approach is to consider an infinitesimal plane wave and study the sound field that is generated as it passes through an inhomogeneous atmosphere. In the present analysis, the shock wave character of the waves is emphasized so that the tendency to flatten out is not lost in the analysis.

P-157
EFFECT OF SST OPERATIONAL MANEUVERS ON SONIC BOOM
G. T. Haglund, E. J. Kane
J. Aircraft, Vol. 9, No. 8, August 1972, pp. 563-568

A comprehensive study of maneuver effects on the sonic boom of an SST-type airplane is presented in this paper. Four types of maneuvers are discussed: pullups, pushovers, longitudinal accelerations beginning at a speed above cutoff Mach number, and longitudinal accelerations through Mach 1.0 to cruise. The analysis is based upon the method developed in an earlier paper by Haglund and Kane (see capsule summary P-119) for determining the effects of maneuvers on sonic boom pressure signatures. That method uses maneuver scaling factors to compute maneuver pressure signatures from known steady-flight signatures. The maneuver scaling factors can be used to calculate the maneuver pressure signatures accurately for a configuration once its steady-flight sonic boom characteristics are known. They can also be used to obtain reasonably accurate quick estimates of the maneuver effects on maximum overpressure.

The following conclusions were reached as a result of this study:

1. Maneuver effects are not necessarily significant for large supersonic airplanes. This is because of the normal operating characteristics (Mach number, altitude, and maneuver-load limits). The maneuver effects are most significant at the low supersonic Mach numbers, where caustics can be produced within the permissible load limits. Thus it may be necessary to place constraints on maneuvers at low supersonic Mach number to ensure the avoidance of significant maneuver effects and caustics.

2. The transition from subsonic to supersonic flight where the acceleration through Mach 1 produces a caustic on the ground will be the most important maneuver in SST-type operations. The intensified shock waves cover only a very small area however. Using modern methods of flight-path control, these can be placed with reasonable accuracy in a specific location.

3. Methods have been devised for calculating detailed pressure signatures near caustics. However, the signature at the caustic cannot be calculated by present linear theories. The location of caustics on the ground can be predicted with good accuracy.

4. Longitudinal accelerations lead to slightly longer pressure signatures with stronger shock waves.

5. The pressure signature increases in length and shock waves are weaker during pullups than in steady, level flight For pushover maneuvers, the opposite is true, in general.

6. Airplane climb angle has a significant effect on shock wave strength during pullups and pushovers. Except at the low supersonic Mach numbers, these effects are small for operational maneuvers.

This paper does an excellent job of isolating potential problem areas resulting from maneuvers of SST-type aircraft.

P-158
CLOSED FORM SOLUTION FOR THE SONIC BOOM IN A POLYTROPIC ATMOSPHERE
R. Stuff
Journal of Aircraft, Vol. 9, No. 8, August 1972, pp. 556-562

In this paper solutions are derived for singularities in a polytropic atmosphere. The sonic boom of a body in supersonic flight is obtained analytically using the analytic method of characteristics (see capsule summary G-72) A parabolic arc body is chosen as an example, and Whitham's asymptotic formula (see capsule summary G-3) for the bow shock overpressure is improved by an explicit formula giving sufficiently accurate results for distances of about 20 body lengths or larger.

A rigorous derivation is made of the shock wave propagation below the flight path. Several other applications of the analytic first-order solution are also presented.

P-159
A DETERMINISTIC MODEL OF SONIC BOOM PROPAGATION THROUGH A TURBULENT ATMOSPHERE
B. H. K. Lee and H. S. Ribner
National Research Council of Canada, Aeronautical Report LR-566, November 1972

In this paper an idealized model of turbulence is used to study the propagation of a weak normal shock wave through a turbulent atmosphere. The field of turbulence is assumed to be weak and is represented by the superposition of two inclined shear waves of opposite inclination to the mean flow. This results in a flow having a cellular nature, the cells being rectangular in shape. The direction of flow rotation alternates from cell to cell.

It is shown that if the angles between the normals of the incident shear waves and the direction of the mean flow are greater than some critical value an exponentially decaying pressure wave is generated behind the shock. By adding or subtracting this pressure wave from the steady state pressure field, "spiked" or "rounded" waveforms are obtained.

An example calculation showed that for moderate turbulence wind velocities (peak velocities on the order of 70 m.p.h.) and for weak shocks typical of those in sonic booms, the equations used in this analysis predict overpressure fluctuations on the order of plus or minus 50%, according to whether the waves are "spiked" or "rounded".

The following weaknesses of the theory described in this paper are pointed out by the authors:

1. The heights of the "spikes" appear to be predicted reasonably well, but the widths are not.

2. The theoretical model is limited to very weak turbulence velocities when the shocks are very weak. This is a result of the basic assumption that the flow be supersonic everywhere upstream of the shock. Thus the example problem used the equations well outside their range of validity. However, it was felt that the example should be adequate to demonstrate qualitative behavior.

3. The simulation of the turbulence as a cellular flow in long, narrow boxes may not be adequate.

Crow (see capsule summary P-79) and Pierce (see capsule summary P-80) also proposed theories to explain the "spiking" and "rounding" of N-waves. Their theories were based upon a statistical description of the turbulence in contrast to the regularized model of turbulence used in the present paper.

P-160

DISTORTION OF NEAR-SONIC SHOCKS BY LAYERS WITH WEAK THERMAL FLUCTUATIONS

L. S. Taylor and R. E. Phinney

Journal of Sound and Vibration, Vol. 25, No. 4, 1972, pp. 623-631

The derivation carried out in this paper is nearly the same as that made in another paper by Phinney and Taylor (see capsule summary P-156) except that in the present derivation the turbulent velocity fluctuations upstream of the shock are ignored. This eliminates the necessity of transforming to randomly moving coordinates which make the velocity in front of the shock appear to be zero, and then transforming back to fixed coordinates to establish the shock properties. The reader is referred to capsule summary P-156 for a more detailed discussion of this work.

P-161

GODUNOV-METHOD COMPUTATION OF THE FLOW FIELD ASSOCIATED WITH A SONIC BOOM FOCUS

L. W. Parker and R. G. Zalosh

AIAA Paper No. 73-240, Presented at AIAA 11th Aerospace Sciences Meeting, Washington, D. C., January 10-12, 1973

In this paper a modification of a method due to Godunov (see: S. K. Godunov, A. B. Zabrodin, and G. P. Prokopov, "A Difference Scheme for a Two-Dimensional Problem in Gas Dynamics and the Calculation of a Flow with a Detached Shock Wave", USSR, Computational Mathematics and Mathematical Physics 1, pp. 1187-1219 (1962)) is used to compute the flow field associated with a sonic boom focus. The method used here employs a shock-following mesh where the grid points move with the N-wave. This scheme confines the grid points to the continually changing region of interest between the front and rear shocks and close behind the rear shock. A cell is associated with each grid point, and the conservation equations of fluid mechanics are applied to these cells. By assuming the flow variables to be independent of position in the interior of the cell or on any given cell-boundary surface area, difference equations are obtained. These equations are used to update the flow variables in a time-step interval Δt. The time-step interval is limited by a stability criterion to a time less than that required for an acoustic signal to travel across any cell.

The solution of one-dimensional Riemann problems forms the basis for the Godunov procedure. The Riemann problem describes the manner in which a discontinuity between two regions of constant flow evolves with time. Two such regions may be within two adjacent interior cells or on both sides of a shock segment; thus, there are four Riemann problems associated with each cell. The solution of the Riemann problems is described within the present paper.

The solution is used in conjunction with the previously described difference equations to obtain the complete solution for the changing flow field quantities in the vicinity of the shock wave.

In order to illustrate its application, the method is applied to a few sample problems. These include cold-spot refraction-focusing and a shock front with an analytically prescribed concavity.

In the cold-spot problems the radius of the spot was assumed to be equal to 150 meters. The solutions obtained were for an initially planar N-wave with a wavelength of 50 meters and a nominal overpressure, $\Delta P_0/P_0$ of 1/1000. It is shown that focusing does take place and the pressure signature of the N-wave is shown to become sharply spiked in the focal region. It is also shown that, for realistic atmospheric temperature inhomogeneities, the focus factors should be less than 2.

For a shock front with an analytically prescribed concavity, it is shown that strong shocks straighten out without cusping, whereas converging concave weak shocks become cusped upon focusing, as in the cold-spot problem. Both in this case of focusing and for the cold-spot focusing, the cusp is shown to decay asymptotically downstream of the focus.

The results of this investigation concerning cold-spot focusing lend support to Pierce's theory of the atmospheric spike producing mechanism (see capsule summary P-80).

The most important finding of this investigation was that of the behavior difference between concave strong and weak shocks. Although the method presented here does appear to give reasonably valid solutions at a focus, it may be too cumbersome to be of much use in actual engineering practice.

The example problems used here deal only with the focus resulting from a three-dimensional concavity in a shock. These problems are more of academic rather than of practical interest.

P-162

FLIGHT TEST MEASUREMENTS AND ANALYSIS OF SONIC BOOM PHENOMENA NEAR THE SHOCK WAVE EXTREMITY

G. T. Haglund, E. J. Kane

NASA CR-2167, February 1973

This report presents an analysis of flight test measurements obtained in a test program conducted at Jackass Flats, Nevada, during the summer and fall of 1970. The program consisted of 121 sonic-

boom-generating flights over the 1529-ft BREN tower. This test program was designed to provide information on several aspects of sonic boom, including caustics produced by steady flight near the threshold Mach number, caustics produced by longitudinal accelerations, sonic boom characteristics near lateral cutoff, and the vertical extent of shock waves attached to near sonic ($M < 1.0$) airplanes. In this report the measured test data (except for the near-sonic flight data) were analyzed in detail to determine the accuracy and the range of validity of linear sonic boom theory.

The following are the main findings of this investigation:

1. Overpressure increases measured at caustics produced during threshold Mach number flight, compared to the overpressure produced during steady, level flight at about Mach 1.2, were relatively low, ranging from about 1.0 to 1.8 except in one case where it appeared that small-scale atmospheric turbulence produced "spikes" on a caustic signature.

2. Caustics were also produced by small inadvertent changes in the airplane speed during several of the "steady," level threshold Mach number flights. These caustics were slightly stronger than those produced during threshold Mach number flights, with a maximum amplification factor of about 3.

3. Measured overpressures at caustics produced by airplane accelerations beginning from Mach 0.95 ranged from 2 to 5 times those which would be observed during steady, level flight at about Mach 1.2.

4. Pressure signatures were also observed near lateral cutoff which resembled those measured at caustics. These disturbances were of very low intensity, however, less than one-half the intensity beneath the flight path.

5. The distinguishing features of pressure signatures near caustics are the "U" shape of the signature, about a 40% longer duration than normal, and the sharp peaks at the bow and tail shocks. Some typical signatures near a caustic are shown in the figure below.

6. Comparison of theoretical calculations with the observed data showed good agreement in all cases where it was possible to make such calculations. Shock wave intensities agree reasonably well, as do signature shapes when the effects of small-scale turbulence are neglected in the observed data. Shock wave arrival times can be predicted within 1.0 sec. Caustic locations during transonic acceleration and lateral cutoff locations can be predicted to within 3300 feet.

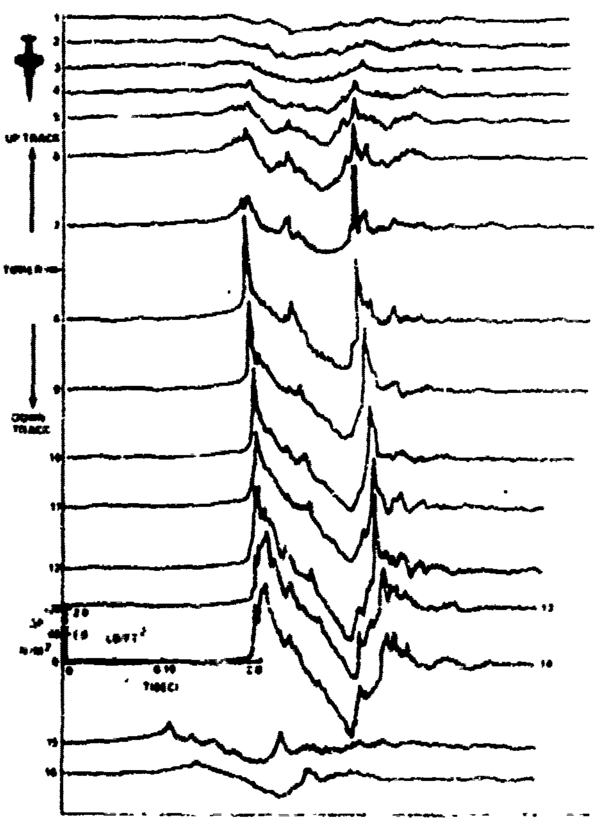
7. The linear theory is invalid within about 330-660 feet vertically above caustics and where the shock wave is within a few degrees of the cutoff condition.

8. Analysis of the rumble data produced during flight near the threshold Mach number showed that "low rumbles" occurred when the airplane ground speed was at least 20 ft/sec lower than the maximum shock propagation speed.

9. The ground reflection coefficient was calculated for a number of cases, and the data indicate a gradual decrease from about 2.0 to 1.0 near the cutoff condition. This is in direct contrast to several theoretical studies which predict an increase to 3.0 near cutoff.

10. A characteristic of sonic boom disturbances near the cutoff condition is the presence of "precursors" or pressure pulses that propagate ahead of the basic pressure signature. Precursors were produced during the threshold Mach number flights and the lateral cutoff flights when shock waves were near the cutoff condition, and thus propagating at speeds close to the local propagation speed parallel to the ground.

11. During the threshold Mach number flights and the lateral cutoff flights, considerable information was obtained on the acoustic disturbances that occur past the cutoff condition. Generally, these disturbances propagate at the local speed of sound rather than the airplane ground speed. By detailed analysis of these data it was possible to isolate the effect of the presence of water vapor on the propagation speed. An increase was noted, in agreement with theory. For low supersonic flight and when the increase in propagation speed is 3 ft/sec or more, this effect should be taken into account.



Ground Pressure Signatures Near Caustic-Ground Intersection

In another investigation, Wanner et al. (see capsule summary P-155) obtained results for the overpressures at a focus or superfocus caused by linear acceleration, entry to turn, pushover, or a turn. Their results for linear acceleration were in essential agreement with those of the present report for the overpressure magnification factor at the focus (about 5). The rest of their results complement those of the present paper.

This is a very significant paper in that the overpressures at caustics cannot yet be accurately predicted due to the nonlinear effects that predominate there. This paper, along with that of Wanner et al., forms nearly the entire basis for what is definitely known concerning the overpressures at caustics.

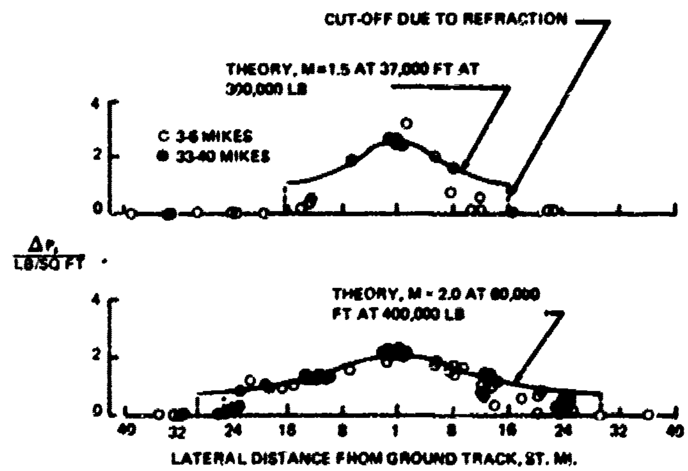
P-163

PRELIMINARY RESULTS OF XB-70 SONIC BOOM FIELD TESTS DURING NATIONAL SONIC BOOM EVALUATION PROGRAM

D. J. Maglieri, V. Huckel, H. R. Henderson, and T. Putnam.

Sonic Boom Experiments at Edwards Air Force Base, Interim Report, NSBEO-1-67, Annex C, Part II, July 28, 1967

This report documents the measurements made from XB-70 sonic boom flight tests made as part of the Edwards Air Force Base sonic boom experiments. Included are brief descriptions of the test area, the instrumentation deployment plan, the flight track, and aircraft operating conditions, as well as presentation of sample data and preliminary conclusions of data analysis. Data were obtained for a series of 20 flights of the XB-70 airplane for the Mach number range 1.38 to 2.94, for the altitude range from 31,000 to 72,000 feet, and for a gross weight range of about 300,000 to 420,000 lbs. The figure below, which was taken from this report, shows the values of overpressure measured at various lateral distances from the flight track.



Sonic boom overpressures for the XB-70 airplane as a function of lateral distance for two different flight conditions

The measured results showed the signature shape variations and the associated variations in overpressures, impulses, and time durations to be similar in nature to those observed previously for smaller airplanes. Variability in the above quantities was markedly greater in June than in the November-January time period and was thus believed to be related to atmospheric effects. For cases where a large number of overpressure data points were available, the average measured values correlated well with current theory.

The results found here, which showed that the overpressure was relatively small in the cutoff regions, even for flight altitudes of 60,000 feet, do not provide any support for the predictions made by Lundberg, et al. (see capsule summary P-169) of the possible occurrence of large magnification factors in the cutoff region, especially for flight at high altitudes.

P-164

GROUND CONFIGURATION EFFECTS ON SONIC BOOM

Dino Dini and Renzo Lazzeretti

AGARD Conference Proceedings No. 42, Aircraft Engine Noise and Sonic Boom, May 1969, pp. 25-1 thru 25-29.

This paper presents a very general discussion of ground configuration effects on sonic boom intensities. It is shown that from a general point of view, the ground configuration regarding large areas has no predominant effect on sonic boom. Some sort of multiple echoes on rough ground, building-populated areas, and mountain peaks and cavities may considerably amplify the intensity of sonic booms. But, essentially, any large magnifications in sonic boom intensity that may occur are concentrated in small regions.

For a more extensive and quantitative discussion of the intensification factors that can result from ground and building configuration effects, see capsule summary P-113.

P-165

FOCALIZATION IN SHORT NON-LINEAR WAVES, APPLICATION TO BALLISTIC NOISE OF FOCALIZATION

J. P. Guiraud

NASA TT F-12,442, Sept. 1969

Sonic boom propagation is described mathematically in this paper, with particular emphasis being placed on the phenomenon of focusing. Equations are derived which give the perturbation velocities in the region near a focus, and it is shown that these equations can be reduced to a Tricomi equation. It is pointed out, however, that when the short wave chain which approaches the caustic curve is associated with a nonlinear physical phenomenon (such as an N-wave) peculiarities arise in the solution of the system of equations. It is hypothesized that these peculiarities will only be overcome by a numerical procedure involving similarity considerations at the caustic.

Seebass (see capsule summaries P-145 and P-146) also has investigated nonlinear acoustic behavior in the vicinity of caustics.

P-166

THE LOCATION OF THE GROUND FOCUS LINE PRODUCED BY A TRANSONICALLY ACCELERATING AIRCRAFT

J. H. Nicholls and B. F. James

Journal of Sound and Vibration, Vol. 20, No. 2, 1972, pp. 145-167

This paper presents an extensive investigation of the location of the ground focus line produced by

a transonically accelerating aircraft. The theory of sonic boom propagation in a horizontally stratified atmosphere with winds is described and is utilized to derive a computer program for finding, for an aircraft accelerating and climbing normally along a straight line ground track, the location of the intersection of the sonic boom wavefront with the ground. The locations of the ground focus line are then found for a large range of atmospheres. By assuming simplified atmospheric structures, relationships are then derived between "focusing" Mach number M_f (Mach number of aircraft at which the apex ray of the focus line originates), and each of the following: cut-off Mach number M_c, the distance, D_f, travelled by the airplane in reaching M_f, the distance S_f travelled by the wave front along the apex ray, and the lateral extent of the focus line. The possibility of forecasting the location of the focus line is also considered, together with the possibility of defining an area on the ground which would encompass all focus lines for a given flight plan. In a later remark on this paper (see capsule summary P-167 Haglund and Kane show that the theory used in the present paper is equivalent to that of Hayes (see capsule summary P-98). Also presented in that note are the results of a flight test experiment which substantiates the results predicted by the Hayes computer program, and which, therefore, also substantiate the validity of the theory of the present paper.

P-167

REMARKS ON THE PAPER BY J. M. NICHOLLS AND B. F. JAMES "THE LOCATION OF THE GROUND FOCUS LINE PRODUCED BY A TRANSONICALLY ACCELERATING AIRCRAFT"

G. T. Haglund and E. J. Kane

Journal of Sound and Vibration, Vol. 24, No. 4, 1972, Letters to Ed., pp. 1-5

This short note comments on the paper by Nicholls and James (see capsule summary P-166) and also on a previous paper by Nicholls (see capsule summary TM-10). It also presents some data from flight experiments conducted in Nevada using the BREN tower (see capsule summary TM-13 which confirm the validity of using geometric acoustics for predicting the location of focus lines.

In the paper described in capsule summary TM-10 Nicholls noted an apparent discrepancy between his derivation of an expression for the threshold Mach number and the results of earlier work by Kane and Palmer (see capsule summary P-42). It is shown in the present comment that both are the same and that the differences are mainly algebraic in nature due to differences in the coordinate system initially assumed.

A comparison of numerical results for the caustic location obtained using the method given in the later paper of Nicholls and James with those obtained using the method of Hayes, et al (see capsule summary P-98) is then made. It is found that the results are essentially the same.

Flight-test measurements of the caustic location resulting from transonic acceleration, made using the BREN tower in Nevada, are then compared with the results predicted using the method of Hayes, et al. It is shown that the agreement between theory and experiment is good. For a further discussion of the BREN tower flight measurements see capsule summary TM-13)

P-168

DISTORTION OF NEAR-SONIC SHOCKS BY LAYERS WITH WEAK THERMAL FLUCTUATIONS

L. S. Taylor and R. E. Phinney

Journal of Sound and Vibration, Vol. 25, No. 4, 1972, pp. 623-631

This paper presents a theoretical investigation of focusing effects of random temperature and pressure variations on the propagation of weak shock waves. An extension of Whitham's theory of shock dynamics (see capsule summaries P-17 and P-22) forms the basis of the theoretical procedure used. An important simplifying assumption is made in which the velocity fluctuations upstream of the weak shock are ignored and only the thermodynamic fluctuations are considered. This was done to avoid the necessity of transforming to randomly moving coordinates which make the velocity in front of the shock appear to be zero, and then transforming back to fixed coordinates to establish the shock properties.

The result of the analysis is a non-linear partial differential equation for the function α which describes the shock motion. This equation is then solved using a perturbation procedure. The final result is an expression for the pressure fluctuation behind the shock. For turbulence at sea-level conditions, the equation gives a pressure fluctuation on the order of 1 psf.

The present investigation, as pointed out by the authors, is complementary to the previous investigations of Crow (see capsule summary P-79), George and Plotkin (see capsule summary P-124), and Pierce (see capsule summary P-80). This was the first attempt made to solve the shock turbulence problem using Whitham's theory of shock dynamics. It is pointed out by the authors that the advantage of this method is that the shock is treated realistically even though it may be very weak. By not ignoring the variation in propagation velocity, a disturbance of shock shape and the related alteration in strength is allowed. The authors also point out that, although the analysis is limited to the context of Whitham's theory, it has the advantage of a less ambiguous mathematical development than has been possible in the second order theories and yields results which are in reasonable agreement with observed pressure perturbations.

In another paper (see capsule summary P-156) Phinney and Taylor performed a similar investigation, except in that case velocity perturbations ahead of the shock were allowed.

P-169

ATMOSPHERIC MAGNIFICATIONS OF SONIC BOOMS IN THE OKLAHOMA TESTS

Bo K. Lundberg, Robert F. Dressler, and Sven Lagman

FFA Report 112, 1967

This report makes use of the data obtained in the Oklahoma City sonic boom tests (see capsule summary S-15) to perform a statistical investigation of atmospheric magnification of sonic booms. The "magnifications" consist of sharp spikes superimposed on the normal N-wave signature and are due to atmospheric turbulence which occurs near the ground. The procedure used in this investigation consisted of the following four steps: (1) the cumulative frequency dis-

tributions of local ΔP (overpressure) magnifications for stations at 0, 5, and 10 miles from the flight track for each of the two airplanes used in the tests were taken from the Oklahoma City report (see capsule summary S-15); (2) the straight-line distribution for each station was then shifted so that a local magnification of 1 corresponded to a 50% probability of being exceeded; (3) local overpressure magnification was then plotted versus y/H for various probabilities of occurrence.

The increase in overpressure magnification with flight altitude is then investigated. Curves of overpressure magnification versus altitude are plotted for the altitude range of 25,000 to 70,000 feet. However, at altitudes above 40,000 feet the curves are merely extrapolations which have no experimental basis. These extrapolations indicate that the overpressure magnification factors will increase significantly with increasing altitude, especially in the region of lateral cutoff. The same trend was found for the signature impulse.

The Oklahoma City flights were made in the jet stream. This wind influence is not present at higher altitudes. As a result, the extrapolations made in this paper are invalid. This has been borne out by the results of subsequent flight test investigations (see capsule summary P-141, for example).

P-170

LABORATORY SIMULATION OF DEVELOPMENT OF SUPER-BOOMS BY ATMOSPHERIC TURBULENCE

H. S. Ribner, P. J. Morris, and W. H. Chu

The Journal of the Acoustical Society of America, Vol. 53, No. 3, 1973, pp. 926-928

This paper presents the results of a laboratory simulation of turbulent-distortion of N-waves. The turbulence was simulated by an air jet in the UTIAS 80-ft sonic boom generator horn (see capsule summary SM-17). The jet was arranged so as to blow either against or with the direction of boom propagation.

The results showed that the effect of the jet flow on the pressure signature of an N-wave travelling against the flow was to produce a spiked pressure signature closely resembling that resulting from supersonic flight in a turbulent atmosphere. When the N-wave travelled with the flow a rounded signature resulted.

The was the first experiment in which "spiked" and "rounded" sonic boom waveforms were produced in the laboratory by the interaction of N-waves with turbulence. The results of this experiment appear to contradict the conclusion reached by Williams and Howe (see capsule summary P-171) that turbulence cannot cause significant shock thickening.

P-171

ON THE POSSIBILITY OF TURBULENT THICKENING OF WEAK SHOCK WAVES

J. E. Ffowcs Williams and M. S. Howe

Journal of Fluid Mechanics, Vol. 58, Part 3, 1973, pp. 461-480

This paper examines the possible thickening of an initially sharp sonic boom shock wave by atmospheric turbulence. It is shown that the earlier work suggesting turbulence to be the cause of wave thickening (see capsule summary P-124, for example) decribes only the apparent mean diffusion induced by random convection of a sharp wave about its nominal position and thus gives an irrelevant upper bound on wave thickness. In conjunction with wavefront-folding mechanism of Pierce (see capsule summary P-123) it is concluded that, although such a mechanism ultimately accounts for an apparent thickening as individual rays are weakened and tangled by turbulence, this process is too slow to be effective in the practical boom situation. The paper then considers what linear thickening of a wave packet results from propagation through atmospheric turbulence and concludes that, in the relevant limit, a wave may be thickened by a factor of about 2 at most. The resulting conclusion is that atmospheric turbulence cannot be the cause of the thousand-fold discrepancy between the measured wave fronts and their Taylor thickness. Furthermore, it is concluded that the actual cause of the wave thickening is the known tendency for weak shocks to attain a fully dispersed profile owing to non-equilibrium gas effects (see capsule summary P-134).

In an experimental simulation (see capsule summary P-170) Ribner, Morris, and Chu found that "rounded" type sonic boom signatures could be produced by the interaction of an initially sharp N-wave with turbulence. This result would appear to contradict the conclusions of the present paper. More work is obviously required before a firm conclusion regarding the hypothesis of this paper can be made.

P-172

VIBRATIONAL RELAXATION EFFECTS IN WEAK SHOCK WAVES IN AIR AND THE STRUCTURE OF SONIC BANGS

J. P. Hodgson

J. Fluid Mech., Vol. 58, Part 1, 1973, pp. 187-196

In this paper the vibrational relaxation of oxygen and nitrogen is shown to be effective in dispersing weak shock waves in the atmosphere. It is shown that the structure of the waves depends on shock strength, ambient pressure, temperature, and humidity. In cold dry conditions weak shock waves may be several meters wide, whereas stronger shock waves in a hot humid atmosphere may be only a few millimeters wide.

This is a significant paper in that it provides a convincing explanation of the reason for the thousand-fold discrepancy between observed sonic boom shock wave thicknesses in normal undistorted (nonrounded and nonspiked) N-waves and the Taylor value.

4.0 MINIMIZATION

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M-1
THE RELATION BETWEEN MINIMIZING DRAG AND NOISE AT SUPERSONIC SPEEDS
Adolf Busemann
Proceedings of the Conference on High-Speed Aeronautics, Polytechnic Institute of Brooklyn, January 20-22, 1955, pp. 134-144

This paper discusses the far-field overpressures resulting from the lift and volume effects of a body in supersonic flight and the relation between minimizing the wave drag of a body and minimizing the sonic boom intensity. The shock strength in the far-field is calculated for an axially symmetric cone and for a lifting delta wing using linear theory. The calculation shows that the important parameters for the reduction of wave drag--the thickness ratio or total angle of the cone and the chord of the wing--enter into the shock strength equation with the one-fourth power and the altitude enters as the three-fourths power. Because of this it is concluded that progress in minimizing wave drag together with the restriction of supersonic flight to high altitudes is not enough to keep the sonic boom intensity within satisfactory limits.

This is one of the earliest papers to deal specifically with the minimization of sonic booms.

M-2
THE SUPERSONIC BOOM OF A PROJECTILE RELATED TO DRAG AND VOLUME
I. L. Ryhming
Boeing Scientific Research Laboratories, Doc. No. D1-82-0023 Oct. 1959

In this paper the minimum boom of a slender, pointed body of revolution is found, subject to constraining conditions on the bow shock drag and fineness ratio. The body volume effect and the effect of discontinuities in slope of the body meridian section on the boom intensity is also investigated.

The problem dealt with is that of finding the extremes of the quantity

$$T = \int_0^{y_o} F(y)dy$$

when $F(y)$ is subject to the conditions

$$\frac{D}{2\pi q} = \int_0^{y_o} F^2(y)dy = \text{const} = C_1$$

$$\frac{3}{8}\, S(y_o) = \text{const} = C_2$$

and $F(y) \geq 0$ for $0 \leq y \leq y_o$

where

y_o = first zero of F-function (excepting the nose)

D = drag due to bow shock.

The restriction on the F-function rules out all bodies which have a second positive lobe in their F-function which is larger than the first negative lobe. Lagrange's method is then used to find the stationary character of T.

The results show that the asymptotic boom strength, for a given Mach number and altitude, is determined mainly by the length and fineness ratio of the body, the detailed geometry having only second order effects. This agrees with the result found later by Lansing for a larger class of bodies (see capsule summary G-13). For pointed bodies with a given length and fineness ratio it was found that the maximum variation in boom intensity was about ten percent, for a given Mach number and altitude. The principal result is that the minimum wave drag body is also the minimum boom body.

The main drawback to this investigation is that it deals with a restricted class of bodies--those for which only one positive lobe of the F-function contributes to the bow shock strength. Most bodies having subsequent shocks which contribute to the strength of the bow shock are, therefore, not necessarily subject to the conclusions of this report. It is also important to note that this work uses Whitham's asymptotic formula (see capsule summary G-3) and is not valid for the near field.

There is a small error on page 7. It is stated that the F-function for a slender, pointed body is not necessarily zero for $y = 0$. This is incorrect, since, as Whitham showed, $F(y) \sim 2E^2 y^{1/2}$ as $y \to 0$ where E is the nose semi-angle.

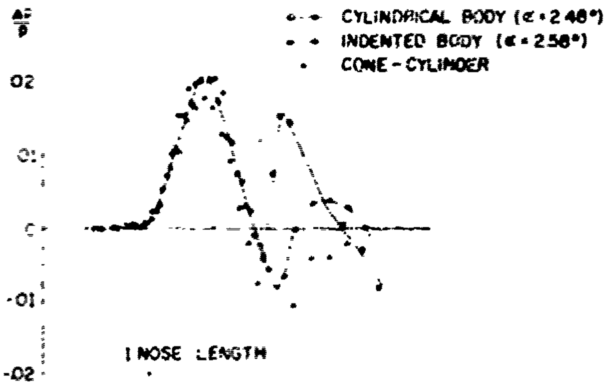
M-3
SUPERSONIC BOOM OF WING-BODY CONFIGURATIONS
I. L. Ryhming and Y. A. Yoler
IAS 28th Annual Meeting Paper No. 60-20 (Jan. 1960)
Also, Boeing Document D1-82-0034, (1959)

The results of an investigation into the possibility of reducing sonic boom strength by making use of the interference between a wing and body are presented. Also included are the results of wind tunnel experiments which substantiate the conclusions reached.

A method is derived for contouring the body so that rearward from the body-wing apex junction the total equivalent body has zero radius. This method uses the expressions derived by Walkden (see capsule summary G-6) for the area distributions of the equivalent bodies of revolution for the body volume, wing volume, lift, and wing-body interference. To get the equivalent body of revolution for the entire wing-body combination, the equivalent area distributions for body volume, wing volume, and lift are added together, and the equivalent area distribution for interference is subtracted from this total. Thus, by designing the body properly, the equivalent area distribution for interference can be made to cancel the sum of the other three components aft of the wing apex. When the body is contoured in such a manner, the only contribution to the boom will be from the body nose ahead of the wing

apex. Thus the contribution of the boom due to lift will be suppressed. This method works only when the boom due to lift is of the same order as the boom due to volume. When lift effects are dominant, the interference effects cannot cancel them.

To check the validity of this method, two models were tested in the Boeing 4' x 4' supersonic blow-down wind tunnel at Mach numbers of 1.41 and 2.00. One model had a conical nose with a cylindrical body and a delta wing, while the other had a conical nose, a delta wing, and an indented body designed to produce no additional boom due to lift up to an angle of attack of 2° at M = 1.41. The figure below, which was taken from this paper, shows that the second peak in the near-field pressure signature, which is due to life effects, is significantly suppressed for the indented body at the design Mach number and angle of attack. For large angles of attack, where lift effects are dominant there was, as expected, no suppression.



Comparison of pressure signatures

The author concludes that the boom due to life can be suppressed by aerodynamic interference as long as the boom due to lift is of the same order as that due to volume. When the boom due to lift is much larger than the boom due to volume, interference becomes ineffective.

This is a good example of the early boom minimization studies, which did not treat lift effects as the dominant factor in boom generation.

M-4
SHOCK WAVE NOISE OF SUPERSONIC AIRCRAFT
I. L. Ryhming, Y. A. Yoler, and Y. Aoki
Society of Automotive Engineers Preprint No. 166B, Presented at the SAE National Aeronautic Meeting, New York, N.Y., April 5-8, 1960

This is a condensed version of an earlier paper by Ryhming and Yoler (see capsule summary M-3). The reader is referred to the capsule summary of that paper for a description of this investigation.

M-5
ON THE GROUND LEVEL DISTURBANCE FROM LARGE AIRCRAFT FLYING AT SUPERSONIC SPEEDS
G. M. Lilley and J. J. Spillman
The College of Aeronautics, Cranfield, Note No. 103, May 1960

This paper discusses the topics of sonic boom generation, structural response to sonic booms, effects of limiting sonic boom overpressure on sonic boom intensity, and sonic boom minimization. Only the minimization concepts are discussed here.

The minimization concept discussed here is based upon a favorable interference between the lift and volume effects of the airplane. If the influence of the wing can be contained in the region $y_0 \leq y \leq \infty$ then the intensity of the bow shock will depend only upon the volume distribution of the airplane. Here y = const refers to the "exact" characteristics as derived by Whitham and y_0 is the value of y for which

$$\int_0^{y_0} F(y)dy$$

is a maximum (see capsule summary G-3 for further explanation of this nomenclature). The intensity of the rear shock will be decreased by favorable interaction between the positive pressure coefficients of the wing and the negative pressure coefficients of the body. It is concluded that by designing the aircraft so that the lift is toward the rear part of the configuration, and by choosing a suitable volume distribution for the airplane, it should be possible to minimize pressure intensities in the far field for a given distribution and a limited range of lift.

Rhyming and Yoler (see capsule summary M-3) conducted a similar investigation into the possibility of using the interference between lift and volume effects to reduce the sonic boom intensity. Their investigation was more quantitative, and it included experimental verification by wind tunnel results. The present report deals only in qualitative terms.

M-6
LOWER BOUNDS FOR SONIC BANGS
L. B. Jones
Journal of the Royal Aeronautical Society, Vol. 65, June, 1961

A derivation of the lower bound for sonic boom intensity due to volume effects, lift effects, and combined effects of lift and volume is presented in this paper. The starting point of the derivation is Whitham's asymptotic formula (see capsule summary G-3) for the bow shock overpressure. In order to minimize that formula it is necessary to determine a minimum of

$$\int_0^{y_0} F(y)dy,$$ where F is Whitham's

F-function and y_0 is the value of y which maximizes the integral (see capsule summary G-3 for further explanation of nomenclature). The expression derived by Walkden (see capsule summary G-6) is used to relate the F-function to the lift and area distributions of the airplane.

The first problem dealt with is that of finding the lower bound for the sonic boom due to lift. This is done by deriving an expression for the total lift in terms of the F-function distribution over the lifting length. The resulting expression shows that the F-function is more efficient in "producing" lift if it is located nearer the apex of the wing than the trailing edge. Therefore, in the limit the lower bound for the sonic boom of a thin wing at given lift is such that the F-curve is zero except at the origin.

The next problem dealt with is that of finding the lower bound for the sonic boom of an aircraft whose design is frozen except that the wing may be cambered and twisted in order to change the chordwise load distribution. It is shown that for this case the F-function for lift should be chosen such that over the rear region, where the F-function due to volume is negative, it is the mirror image of the F-function for volume. If the lift corresponding to this chosen F-function is greater than the weight of the aircraft, it is possible to obtain a total sonic boom intensity which is smaller than that due to volume alone, since this excess lift can be cancelled by taking all the F-function for lift to be negative upstream of the zero at y_o. If on the other hand, the resulting lift is less than that required, it pays, for reasons stated in the previous paragraph, to concentrate this extra positive F-function near the apex of the wing.

The problem of finding the minimum sonic boom due to volume is treated in a similar manner to that of finding the minimum boom due to life. For a slender body of given length, closed at front and with given area at the base, it is found that the distribution of S(x) for the lower bound is $\sqrt{x/\ell}$, except very near the origin. Here s(x) is the cross-sectional area, x is distance from nose, and ℓ is aircraft length. It is shown that the F-function should be chosen such that the positive area is concentrated at the nose and the negative region at the base for the case of a closed body of given length and volume. It is shown that for such a body the minimum value of the F-function integral is given by

$$\int_0^{y_o} F(\eta)d\eta = 3/8\ V/\ell^{3/2}$$

where V = aircraft volume and ℓ = aircraft length.

The final problem treated is that of finding the lower bound for the sonic boom due to volume plus lift. The case considered is that of an aircraft of given length, lift and volume. The F-function for volume is taken as in the previous paragraph. Part of the F-function due to lift should be taken as the mirror image of the negative F-function due to volume. The F-function corresponding to the rest of the lift should be concentrated at the apex of the lifting length.

This is the most important early paper on sonic boom minimization in the far field. The lower bound body shape required to achieve this sonic boom level is quite blunt and is therefore somewhat impractical.

M-7

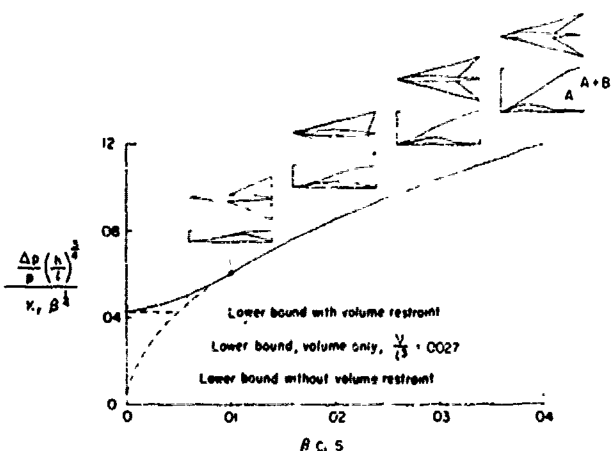
THE LOWER BOUND OF ATTAINABLE SONIC-BOOM OVERPRESSURE AND DESIGN METHODS OF APPROACHING THIS LIMIT

Harry W. Carlson

NASA TND-1494, Oct., 1962

An approximate lower bound of attainable sonic-boom overpressure, which depends only on the airplane length, weight, and volume and on the flight conditions is established in this paper. Whitham's asymptotic formula (see capsule summary G-3) for the bow shock overpressure is used, and the equivalent area distribution for the combined effects of lift and volume (see capsule summary G-6) is varied in order to find a minimum for the bow shock intensity. It is found that the Von Karman minimum-drag body is also the minimum boom body.

It is concluded that this lower bound may be approached over a narrow range of flight conditions through the application of appropriate design considerations. In general, for intermediate values of lift coefficient the major portion of the lift generating surfaces must be located aft of the maximum cross-sectional area, whereas for higher values of lift coefficient the maximum area must be well forward and/or the lift-producing surfaces must extend well toward the airplane nose. These findings are summarized in the figure below, which shows the approximate sonic boom lower bound as a function of lift parameter. The sketches illustrate representative configurations.



Approximate sonic-boom lower bound for an optimum combination of lift and volume

Rhyming and Yoler (see capsule summary M-3) conducted a similar investigation and concluded that the minimum wave drag body is also the minimum boom body. In another investigation (see capsule summary M-5) Lilley and Spillman concluded that by placing the lift distribution toward the rear of the airplane it should be possible to reduce the sonic boom intensity for a limited range of lift, which agrees with the results of the present paper. An absolute far field lower bound was derived by Jones but the shape of the required area distribution was somewhat impractical (see capsule summary M-6).

M-8

CONFIGURATION EFFECTS ON SONIC BOOM
Harry W. Carlson
NASA TM X 905, Proceedings of NASA Conference on Supersonic-Transport Feasibility Studies and Supporting Research, December 1963, pp. 381-398

This paper discusses far-field lower bounds on sonic boom intensities and design methods of approaching this limit. Use is made of the finding by Jones (see capsule summary M-6) that the shape of the equivalent area curve yielding a minimum sonic boom in the far-field is represented by a function in which the area is proportional to the square root of the distance except in the immediate neighborhood of the airplane nose. Theoretical and experimental results of modifying airplane configurations to approach that of the lower bound are then presented. Also included is a discussion of the drag penalties involved in making such modifications. The reader is referred to capsule summary M-9, where a summary of these results is given.

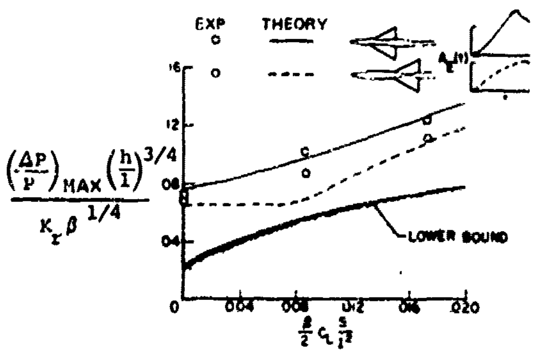
It is concluded that compromises with other design considerations will prevent anything more than a limited approach to lower bound overpressur .

This is a good discussion of far-field lower bound concepts and the problems involved in designing airplanes to achieve lower bound overpressures.

M-9

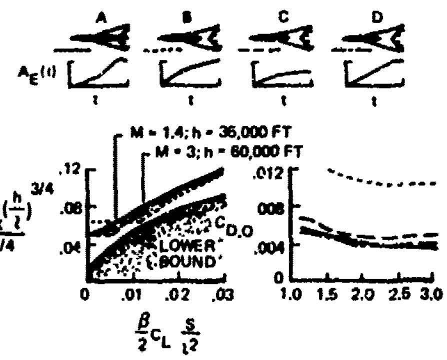
INFLUENCE OF AIRPLANE CONFIGURATION ON SONIC BOOM CHARACTERISTICS
Harry W. Carlson
Journal of Aircraft, Vol. 1, No. 2, March-April, 1964, pp. 82-86

A discussion of lower bound concepts and design methods of approaching this limit are presented in this paper. The finding by Jones (see capsule summary M-6) that the shape of the area distribution curve yielding a minimum sonic boom is a function in which the area is proportional to the square root of the distance except in the immediate neighborhood of the airplane nose is used. The figure below shows a comparison of the bow shock overpressure for a lower bound configuration, a normal aircraft configuration, and a modified configuration whose design approached that of the lower bound. The maximum theoretical reduction in boom strength (about 25%) occurs at the design point and benefits fall off rapidly on either side of that point. The wind-tunnel measured values for the two models show only a part of the theoretical gains, however. It was thought that some of this discrepancy may have been due to boundary-layer and separated-flow effects on the small models.



Experimental study of configuration effects

A theoretical investigation of the effect on drag of designing a configuration for minimum sonic boom was then conducted. The results are summarized in the figure below. Shown in the figure are theoretical sonic boom characteristics and corresponding values of zero lift wave drag for an arrow-wing transport configuration and three modifications. The modifications consisted only of changes in fuselage area distribution. Configuration B, which was modified to approach the sonic boom lower bound for a design point of M = 3 at an altitude of 60,000 feet, required a greatly enlarged forward fuselage with a resultant total airplane volume increase of 60%. This increase in volume resulted in an extremely large zero-lift drag penalty and also showed up as an increase in overpressure for zero lift. Configuration C, with a design point of M = 1.4 at 35,000 feet had a total volume increase of 11%, but still showed a sizable drag penalty. Configuration D was a compromise design, having no volume change, in which an attempt was made to produce a smooth effective-area-distribution curve (similar to that of the area distribution for a minimum-wave-drag body of revolution) for the design point of M = 3, h = 60,000 feet. The decrease in overpressure, which was not as pronounced as for the other two modifications, extended over the whole range of lift coefficients, and only a small drag penalty was shown. It is concluded that compromises with other design considerations will prevent anything more than a limited approach to lower-bound overpressures.



Overpressure-drag relationship for boom-optimized configurations

This paper gives an excellent summary of the state of the art of sonic boom minimization concepts as of 1964.

M-10

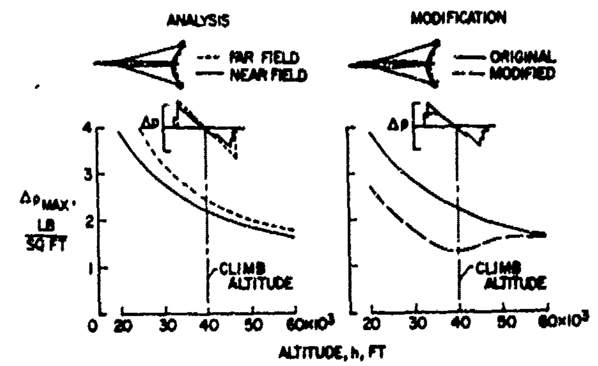
CORRELATION OF SONIC BOOM THEORY WITH WIND TUNNEL AND FLIGHT MEASUREMENTS
Harry W. Carlson
NASA TR R-213, Dec., 1964

This paper presents a summary of the state of knowledge as of 1964 concerning sonic boom generation and minimization. For a discussion of the generation concepts see capsule summary G-25. The section of the paper dealing with minimization concepts is essentially the same as an earlier paper by Carlson (see capsule summary M-9). The reader is referred to the capsule summary of that paper for a discussion of these results.

M-11
DESIGN METHODS FOR MINIMIZATION OF SONIC BOOM PRESSURE-FIELD DISTURBANCES
F. Edward McLean and Barrett L. Shrout
Proceedings of the Sonic Boom Symposium, Acoustical Society of America, St. Louis, Mo., November 3, 1965, pp. S19-S25

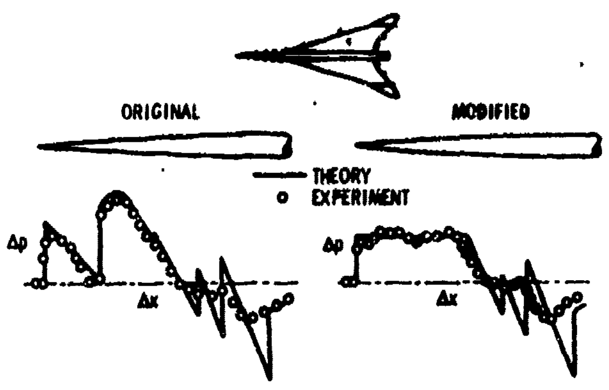
Sonic boom overpressure reductions in the near field are studied in this paper. The investigation is based upon the results of an earlier paper by McLean (see capsule summary G-27) which showed that far-field solutions are not applicable for some normal operating conditions of a large slender airplane, in particular the critical-climb portion of the supersonic transport flight path. For these conditions, the ground pressure disturbance depends upon the shape of the airplane, and the actual ground overpressures are usually less than those predicted by far-field theory. Furthermore, such a pressure signature may be favorably altered by design modifications to the airplane.

To consider the possible reduction of sonic boom overpressure through near-field effects, an arrow-wing transport was analyzed with the general near-field solutions of sonic boom theory (see Whitham's general formula in capsule summary G-3). Furthermore, an analytic modification to the original airplane shape was made to provide a more idealized near-field effective-area distribution. The results of these near-field considerations are shown in the figure below, which was taken from this paper, for a representative climb condition of M = 1.4 and W = 400,000 lb. As indicated by the dashed signature of the right-hand plot, the purpose of the modification was to create a smooth effective area in such a manner as to replace the sawtooth pressure disturbance in the inset sketch with a single bow shock followed by a succession of very weak shocks. The estimated effect of the modification was to reduce the maximum overpressure at the critical climb condition from 2.2 to 1.3 lb/sq ft. It is stated that analytical studies showed that, for this particular application, the near-field modification would have little or no detrimental influence on other aspects of airplane performance. It is pointed out, however, that this might not be true for a similar near-field modification applied to some other airplane.



Near-field effects on climb overpressures

The results of a wind tunnel test using bodies of revolution equivalent to the original and modified configurations are shown in the figure below, which also was taken from this paper. This figure shows that, for both the original and modified shapes, the agreement between theory and experiment is good. The modified shape appears to have the desired effect of replacing the original two-shock system with a bow shock followed by a succession of weak shocks. The maximum overpressures within the modified signature are considerably reduced from those generated by the original shape.



Tunnel signatures from equivalent body representing modified supersonic transport

Wind tunnel results obtained in complete model tests of the original and modified arrow-wing transport showed that the desired signature shapes were approached, but not quite obtained. This was believed to be due to difficulties in constructing small models to exact specifications.

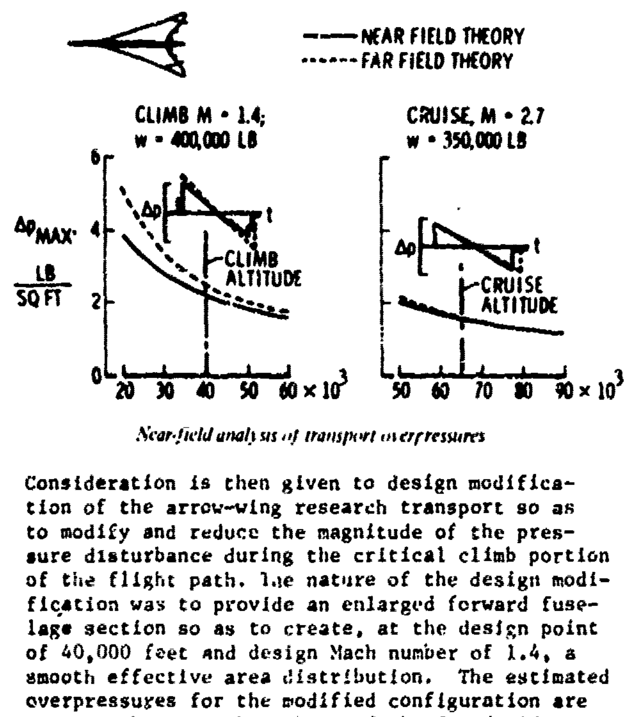
It is concluded that, if low overpressure is a primary consideration in the supersonic-transport operation, near-field effects offer some promise for sonic boom suppression in the critical-climb portion of the flight path.

In an earlier paper (see capsule summary M-6) Jones derived the far-field lower bound body shape. Until McLean introduced his concept of sonic boom minimization through the use of extended near-field effects, it was believed that no overpressures lower than the Jones far-field lower bound could be obtained. Later investigations, such as those by Ferri (see capsule summaries M-24, M-44 and M-58), Seebass (see capsule summary M-37), George (see capsule summary M-41), Jones (see capsule summary M-42), and Seebass and George (see capsule summaries M-53, M-61, and M-62) showed that this is not the case when near-field effects are taken into account. Thus the concept introduced in this paper and earlier papers by McLean, led to a whole new trend in sonic boom minimization efforts.

M-12
THE INFLUENCE OF AIRPLANE CONFIGURATION ON THE SHAPE AND MAGNITUDE OF SONIC-BOOM PRESSURE SIGNATURES
F. Edward McLean and Harry W. Carlson
AIAA Paper No. 65-803, Presented at AIAA/RAeS/JSASS Aircraft Design and Technology Meeting, Nov. 15-18, 1965

The effect of configuration variables and the range of applicability of near-field boom minimization concepts are discussed in this paper. A previous study by McLean (see capsule summary G-27) indicated that for large slender airplanes, such as the supersonic transport, the near-field effects of airplane shape on the pressure signature might extend to the ground. This paper considers the use of these extended near-field effects as a possible sonic-boom minimization procedure.

An arrow-wing transport configuration was analyzed on the basis of both near-field theory (see capsule summary G-3) and far-field theory (see capsule summary G-3, for example). The calculated signatures and maximum overpressures for this transport configuration are shown in the figure below for two representative operating conditions. Somewhat lower overpressures (about 10 percent) are indicated by the more applicable near-field solution in the critical climb or acceleration case. The near-field effects are negligible at altitudes and weights associated with the cruise Mach number of 2.7, however. Since the climb portion of the transport flight path is the most critical from sonic boom considerations, the reductions indicated by the near-field analysis of this flight regime are significant.



Near-field analysis of transport overpressures

Consideration is then given to design modification of the arrow-wing research transport so as to modify and reduce the magnitude of the pressure disturbance during the critical climb portion of the flight path. The nature of the design modification was to provide an enlarged forward fuselage section so as to create, at the design point of 40,000 feet and design Mach number of 1.4, a smooth effective area distribution. The estimated overpressures for the modified configuration are shown to be less than those of the far-field lower-bound of overpressures.

A wind tunnel investigation was then conducted using four-inch airplane models of the original and modified transport configurations. Also included were equivalent bodies of revolution representing the airplane effective area distributions at the design Mach number of 1.4, design weight of 400,000 lbs, and design altitude of 40,000 feet. The results obtained using the equivalent bodies are shown in the second figure in capsule summary M-11. The modified shape is seen to have the desired effect of replacing the original two-shock system with a single bow shock followed by a succession of weak shocks. The results obtained using the complete airplane models did not show quite the same degree of correlation with theory as did the equivalent body results. The trends were quite similar, however. It is concluded that the near-field boom minimization concept may have useful application in the critical transonic portion of the supersonic transport flight path.

In an earlier investigation (see capsule summary M-9) into the influence of airplane configuration on sonic boom characteristics Carlson concluded that compromises with other design considerations would prevent anything more than a limited approach to lower-bound overpressures. However, no account was taken in that investigation of near-field effects. The present investigation shows that when near-field effects are taken into account, sonic boom intensities lower than those of the far-field lower bound may be attainable for certain flight conditions.

M-13

A WIND TUNNEL STUDY OF SONIC-BOOM CHARACTERISTICS FOR BASIC AND MODIFIED MODELS OF A SUPERSONIC TRANSPORT CONFIGURATION

Harry W. Carlson, F. Edward McLean, and Barrett L. Shrout

NASA TMX-1236, May 1966

This report presents the results of a wind tunnel study which verified the use of near-field concepts to modify sonic boom pressure signatures. Basic and modified models of a supersonic transport configuration having an overall length of 10 cm were tested in the Langley 4- by 4-foot supersonic wind tunnel at Mach numbers of 1.41 and 2.01. The modified model was designed using Whitham's general (non-asymptotic) theory (see capsule summary G-3) to have a flat top pressure signature.

Equivalent bodies of revolution representing the basic and modified models were also tested in the wind tunnel. It was found that the agreement between experiment and theory was good.

This was a very significant wind tunnel investigation since it was the first to demonstrate the validity of using near-field effects to modify sonic boom pressure signature shapes. These wind tunnel results are also discussed in earlier papers by McLean and Carlson (see capsule summary M-12) and McLean and Shrout (see capsule summary M-11).

M-14

SONIC-BOOM CHARACTERISTICS OF PROPOSED SUPERSONIC AND HYPERSONIC AIRPLANES

F. Edward McLean and Harry W. Carlson

NASA TN D-3587, September 1966

This paper explores the use of near-field effects to modify the sonic booms of large, heavy supersonic and hypersonic airplanes. It also relates the predicted sonic boom characteristics of such airplanes to those of the supersonic airplanes that were operational at the time the report was written, but for a summary of this discussion see capsule summary SBA-8.

It is shown that by making use of the near-field characteristics of large airplanes the sonic boom pressure signatures during the early climb and acceleration phases of flight can be modified significantly to obtain either a lower overpressure or a finite rise time. The increased altitude at which cruising flight takes place makes the use of near-field effects less effective in modifying the shape of the pressure signature during cruise; however, it is shown that by increasing the airplane length, near-field effects can become important for this case, also. The area modifications required to obtain the finite-rise-time and plateau-type pressure signatures are discussed, and wind tunnel results are presented which demonstrate that a model modified to produce a plateau-type pressure signature actually did, to a close approximation, generate the desired signature. The results of this wind tunnel test were also discussed in the papers summarized in capsule summaries M-11, M-12, and M-13.

M-15
SONIC BOOM ANALYSIS
Richard K. Koegler
AIAA Paper No. 66-941, presented at AIAA Third Annual Meeting, Boston, Mass., Nov. 29-Dec. 2, 1966

In this paper a survey is made of the SST sonic boom problem with respect to the phenomena of shock wave decay and aural response and their relation to SST configuration constraints and flight performance characteristics. Means of alleviating the effects of sonic booms on supersonic transport design are explored, largely on the basis of Lighthill's viscous wave studies and Whitham's theory (see capsule summary G-3). It is shown that SST overpressure ratios near the aircraft in cruise flight and altitude effects on viscosity are large, resulting in the conclusion that the shocks may decay more rapidly than predicted by Whitham's theory. The phenomenon of high decay rates in intermediate shocks (see capsule summary M-21) is also discussed, along with the use of near-field effects to reduce human aural response.

M-16
LOWER BOUNDS FOR SONIC BANGS IN THE FAR FIELD
L. B. Jones
The Aeronautical Quarterly, Vol. 18, Feb., 1967, pp. 1-21

Far-field lower bounds are obtained in this paper for the intensity of the sonic boom resulting from a slender aircraft flying straight and level at supersonic speeds. The lower bounds are obtained for an aircraft subject to various constraints on its total lift, volume, area distribution, and center of pressure position. In all cases the length of the aircraft is taken as fixed. Also, in the appropriate cases it is assumed that the body or aircraft is closed at the nose. The pressure jump across the shock wave is taken to be that given by the Whitham-Walkden theory (see capsule summaries G-3 and G-6).

The central problem dealt with is that of finding a minimum of

$$J = \int_0^{y_0} F(\eta)\, d\eta \text{ given certain con-}$$

straints on $F(\eta)$. This is done for non-lifting bodies, a lifting wing without volume, and for a general configuration. The results are summarized in tables which present the physical quantities constrained in each case, the minimum values of J, and any necessary conditions.

The work described in this paper proves the results quoted in an earlier paper by Jones (see capsule summary M-6) and extends the results to cover more constraints, mainly the center of pressure position.

M-17
SONIC BOOM REDUCTION
Adolf Busemann
NASA SP-147, Sonic Boom Research, 1967, pp. 79-82

A brief investigation into the use of quadrupoles to reduce sonic boom intensities is presented in this paper. The purpose of using the quadrupoles is to design the airplane lifting surface so as to "suck more toward the sky and press less toward the ground."

It is shown that the representation of the aircraft configuration by quadrupoles requires a strength distribution along the center of the airplane, the second derivative of which is the sink effect toward the ground. Two means of physically realizing such a quadrupole distribution in an airplane configuration are then discussed briefly. The first of these was the use of conical shapes, such as delta wings or cones, with common tip pushing the air, one to the right and the other one to the left, horizontally. The free space opening between them is supposed to suck in air vertically. The pair of circular cones were used in calculations and experiments. The criterion was to find a zero pressure at the Mach cone in the vertical direction and a high pressure created by the yawing pair of cones in the horizontal plane. The theoretical result furnished such a distribution, but the experiment check did not sufficiently support this result.

The second configuration discussed is the ring wing. This configuration is shown to be a step toward solving the problem created by the relationship between a strong near-field and a weaker field farther out that always appears as a stumbling block when looking for effects in the far field by shaping bodies near the axis. However, the disturbance waves which travel toward the center of the ring wing create a very complex situation which is difficult to analyze.

George made a more extensive investigation of the use of quadrupole effects to achieve sonic boom reductions (see capsule summary M-23). However, the present paper was the first to suggest such a technique.

M-18
BRIEF REMARKS ON SONIC BOOM REDUCTION
Antonio Ferri
NASA SP-147, Sonic Boom Research, 1967, p. 107

This is a very brief comment on the reduction of sonic boom due to volume and lift effects. In connection with volume effects it is pointed out that those can, in principle, be eliminated by the Busemann biplane criteria generalized to three-dimensional flow. Some engine cycles can

also be effective in reducing the sonic boom due to volume, especially at high Mach numbers. It is stated that the effect of lift can be reduced by distributing lift over a large area. Multiplane configurations where the negative leg of the N-wave is used to reduce the positive leg of the N-wave produced by the following wing can also, in principle, reduce to sonic boom due to lift.

Ferri expands upon the lift-reduction concepts in a later paper (see capsule summary M-24).

M-19
THE POSSIBILITIES FOR REDUCING SONIC BOOM BY LATERAL REDISTRIBUTION
A. R. George
NASA SP-147, Sonic Boom Research, 1967, pp. 83-93

An analysis of the possibility of reducing sonic boom overpressure on the ground by laterally redistributing the aircraft disturbance pressure field is presented in this paper. This pressure redistribution is accomplished through the use of multipoles. Lateral redistribution of disturbances can be used to reduce the boom on the ground because disturbances in other than vertical planes travel a longer distance and are thus attenuated more before reaching the ground.

The multipole solutions are obtained from a formal Laplace transform treatment of the perturbation potential equation. The solutions are expressed in terms of the Mach number, distance from the body axis, and the characteristic variable. Some possible means of exciting higher order multipoles are discussed. These include a flat plate wing (dipole), multiple wing-like surfaces (quadrupole), and a configuration of two slender cones joined at their apexes (quadrupole). The physical restrictions on the multipole distributions are then derived.

Finally, the increase in wave drag and the decrease in boom due to the addition of a quadrupole distribution is discussed. It was found, for example, that a 17-percent reduction in the boom due to volume can be obtained at the expense of a 5-percent increase in the wave drag due to that volume, while complete elimination of the boom due to volume would require a 50-percent increase in wave drag. It is concluded that the usable boom reduction will depend upon how much additional drag can be tolerated.

A later paper by George is very similar to the present one (see capsule summary M-23). However, the later paper extends the discussion to include a treatment of the desired F-function modifications and physical means of achieving such F-functions through quadrupole additions.

M-20
BRIEF REVIEW OF THE BASIC THEORY
Wallace D. Hayes
NASA SP-147, 1967, pp. 3-7

This paper is concerned, basically, with reviewing sonic boom propagation theory. However, it also touches briefly upon sonic boom minimization, and it is this portion of the paper that is summarized here. For a discussion of the rest of the paper the reader is referred to capsule summary P-73.

The basic point brought out here is that the only essential inescapable parameter controlling sonic boom strength is the total equivalent source strength, which is the sum of three terms. The first term is proportional to the lift times the cosine of the azimuthal angle measured from the direction opposite the lift vector. The second and third terms together correspond to the total net source strength represented by the aircraft system. Since these three terms are generally all of the same sign below the aircraft, the total equivalent source strength connected with the sonic boom can never be zero. Thus the sonic boom below the aircraft is truly inescapable. The best that can be hoped for is that the boom is a minimum for given values of this parameter, with limits on the magnitude of the drag.

M-21
POSSIBLE MEANS OF REDUCING SONIC BOOMS AND EFFECTS THROUGH SHOCK DECAY PHENOMENA AND SOME COMMENTS ON AURAL RESPONSE
Richard K. Koegler
NASA SP-147, Sonic Boom Research, 1967, pp. 95-102

This paper discusses sonic boom minimization through configuration modification. It is conjectured that SST configurations have such complicated F-functions that changes to enhance the decay of intermediate shock waves between the front shock and the rear shock are feasible and might even reduce wave drag.

M-22
ON SUPERSONIC VEHICLE SHAPES FOR REDUCING AUDITORY RESPONSE TO SONIC BOOMS
Walton L. Howes
NASA TMX-52294, 1967

This paper deals with both sonic boom minimization and human response to sonic booms. It is summarized in capsule summary HRSC-32.

M-23
REDUCTION OF SONIC BOOM BY AZIMUTHAL REDISTRIBUTION OF OVERPRESSURE
A. R. George
AIAA Paper No. 68-159, Presented at AIAA 6th Aerospace Sciences Meeting, New York, New York, Jan. 22-24, 1968

An analysis of the use of multipole distributions to reduce a supersonic aircraft's sonic boom is presented in this paper. It is shown that multipole contributions can be important even in the far field and concepts for efficiently exciting them are discussed. The wave drag changes associated with the flow modifications are also treated.

When a basic configuration and its F-curve (see capsule summary G-3) is given, the approach taken in this investigation is to add a quadrupole distribution which is equivalent to a negative closed volume at a point directly beneath the aircraft. This distribution is located so that its initially negative F cancels part of the given F forward of of t_0 (value of t which maximizes

$\int_0^t F(y)dy$), reducing the far

field boom. The distribution is also designed so that its positive F lobe occurs far enough back where it will be compensated by the given F's negative lobes. The F curve is thereby brought more nearly to the Jones minimum boom ideal of a positive delta function at $x = 0$ and a negative delta function at $X = L$ (see capsule summary M-6), where L is the length of the aircraft.

The addition of quadrupole distributions to a specific supersonic transport design was then performed to get an idea of the order of magnitude of the changes in boom and wave drag which could be expected in a practical case. For the first attempt in adding quadrupoles, the boom was reduced by 13% but the wave drag increased by .5%. For the second attempt the quadrupole distribution was modified so as to reduce the drag increase. The resulting boom reduction was 9.6%, while the wave drag increase was 14%.

In agreement with the conclusions of other approaches, it is concluded that the direct effects of lift on the sonic boom cannot be cancelled (this assumes no energy or mass addition or subtraction). However, multipoles can be used to modify the boom signature and overpressure to some extent. Quadrupole distributions are the most useful. The primary problem remaining relative to application of these ideas to practical aircraft is that of relating desired multipole distributions to the exact practical configurations which will produce them.

This investigation relied heavily on the work of Jones (see capsule summaries M-6 and M-16). While Jones' work was directed toward determining the type of F-function which would minimize the sonic boom for a particular configuration, the purpose of the present work was to determine how such an F-function could be achieved.

This paper is nearly identical to an earlier paper by George (see capsule summary M-19). The reader is referred to that capsule summary for additional details of this theory.

M-24
REPORT ON SONIC BOOM STUDIES CARRIED OUT AT NEW YORK UNIVERSITY; ANALYSIS OF CONFIGURATIONS
Antonio Ferri and Ahmed Ismail
New York University, Dept. of Aeronautics and Astronautics, Report No. NYU-AA-68-14, June 1968

The results of an investigation concerning minimization of sonic boom through aircraft configuration modifications is presented in this paper. The following assumptions are made in the analysis: (a) The length of the airplane is kept constant and equal to 300 feet. (b) The weight, altitude and Mach number of flight are kept constant and equal to 465,000 pounds and 60,000 feet and $M = 2.70$. (c) The variations of configurations must not affect too much the drag at the required lift at the flight Mach number. The analysis is limited only to the maximum Mach number of the airplane. Therefore, the configurations obtained are possible configurations for cruise conditions and usually have acceptable transonic qualities.

The main variable investigated is the distribution of lift. It is shown that the maximum overpressure can be reduced below the far-field lower bound of Jones (see capsule summaries M-6 and M-16) if configurations are used that utilize near-field effects. It is also shown that by introducing an appropriate distribution of lift that such effects can be emphasized.

The two main conclusions reached are:

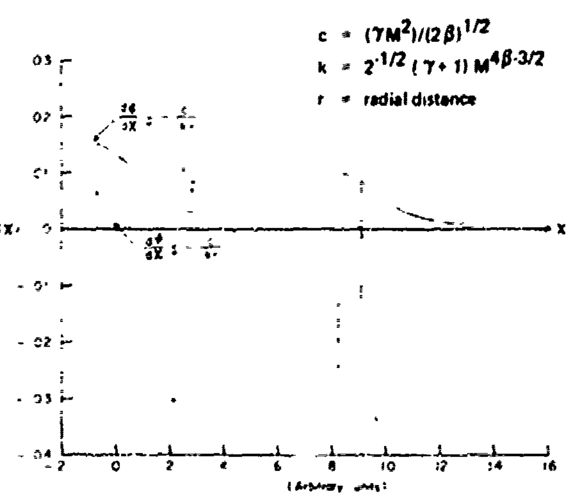
1. Extending the lift distribution over the whole length of the airplane reduces the magnitude of the boom.
2. Carrying more load at the front of the configuration reduces the boom.

Three airplane configurations, designed with the above results in mind are then analyzed, and the maximum overpressure is shown to be of the order of 1 psf. One of these configurations formed the basis of a later experimental investigation by Ferri, Wang, and Sorensen (see capsule summary M-58) whose results verified that the sonic boom overpressure for such a configuration is of the order of 1 psf.

M-25
DESIGN OF BODIES TO PRODUCE SPECIFIED SONIC-BOOM SIGNATURES
Raymond L. Barger
NASA TN D-4704, August 1968

The purpose of this paper is to describe a procedure for designing bodies corresponding to prescribed pressure signatures. The procedure is based upon a step-by-step inversion of Whitham's general (non-asymptotic) method of calculating pressure signatures. The basic steps are as follows:

1. From the pressure signature, a function $\phi(\chi)$ is constructed that can be uniquely related to a generating body. This can be done by constructing equal area lobes intersected by the shocks (see figure below, which was taken from this report). In order to be physically obtainable, the net area of the signature itself must be zero, and the slope of $\phi(\chi)$ must be such that the corresponding function $F(y)$ is not multivalued (but it may have discontinuities).
2. Once $\phi(\chi)$ has been constructed, the function $F(y)$ is obtained using relationships given between y and χ and between F and ϕ.
3. The required area distribution of the body can then be determined by inverting the well-known equation giving F in terms of the area distribution (see capsule summary G-3).



Construction of $\phi(x)$ from given pressure signature

The results of a wind tunnel test are then presented which demonstrate the validity of using this method to design bodies having desired pressure signatures.

It should be remembered that the procedure described in this report is for the case of a uniform atmosphere. The procedure would have to be modified slightly in order to account for the effects of a non-uniform atmosphere.

M-26
SONIC BOOM - A REVIEW OF THE TECHNICAL STATUS
Albert J. Evans
Presented at AIAA 5th Annual Meeting and Technical Display Philadelphia, Pennsylvania, Oct. 22, 1968

This paper presents a general review of sonic boom minimization concepts. Topics discussed include: (1) configuration effects; (2) altitude effects; (3) near-field effects; (4) finite rise time signatures; and (5) exotic schemes involving the use of electrostatic effects or lasers.

M-27
THE FEASIBILITY OF LARGE SONIC BOOM REDUCTIONS
Adolf Busemann
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 125-128

A brief discussion is presented in this paper of the feasibility of large sonic boom reductions. It is shown that the severe restrictions on the allocation of the given total F(x) (Whitham's F-function) for area and lift are a combinationa of the necessity of making lift center and mass center coincide, but under the silent assumption that wing and body are in the same plane. Such a constraint makes the sonic boom footprint the dictator of the airplane design. It is then pointed out that if the possibility of raising the airplane wing high above the body were allowed, the mass center and the lift center would still be in the same vertical line, but the wing abscissa and the body abscissa that create a combined pressure signature are inclined under the Mach angle. Thus, disregarding the silent assumption that wing and nody are coplanar makes it possible to interrupt the fighting between the body tip and the wing, which are additive in F(x), and allow the wing to cooperate with the receding tail end of the body of opposite sign at the latter part of F(x) by making fast exchanges without any pressure creation in the far field. This is given as one example of an application of an unconventional shape to remove severe constraints.

No definite conclusions are reached in this discussion. Its purpose was merely to stimulate thought about the factors which stand in the way of sonic boom reductions so that it can be determined whether these are unescapable restraints of physics or surmountable restraints.

M-28
NOTES ON THE SONIC BOOM MINIMIZATION PROBLEM
Harry W. Carlson
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 185-190

A review of the prospects for sonic boom reduction as of 1968 are presented in this paper. The basis of the discussion is the investigation performed by Carlson in 1962 (see capsule summary M-7) concerning far-field lower bound overpressures and design methods of approaching this limit.

The dependence of the sonic boom intensity on altitude, Mach number, airplane length, and airplane weight is discussed in a general way. It is concluded that maximization of the product of altitude and Mach number consistent with the maintenance of aerodynamic and propulsive efficiency and minimization of the ratio of weight to length consistent with aerodynamic efficiency considerations will lead to sonic boom reductions.

Airplane shaping considerations are then discussed in conjunction with the lower bound overpressure curve derived previously by Carlson (see capsule summary M-7). The shapes discussed here are the same as those shown in the figure contained in that capsule summary. It is pointed out that the elimination of volume effects by the employment of concepts related to the Busemann biplane may not always be advantageous, since volume effects can be combined with lift effects in a favorable fashion to produce lower overpressures than would be the case for the lift alone.

M-29
REPORT ON SONIC BOOM STUDIES
PART I - ANALYSIS OF CONFIGURATIONS
Antonio Ferri and Ahmed Ismail
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 73-88

This paper is exactly the same as the one summarized in capsule summary M-24. The reader is referred to that capsule summary for details of this investigation.

M-30
MULTIPOLES, WAVEFORMS, AND ATMOSPHERIC EFFECTS
A. R. George and A. R. Seebass
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 133-144

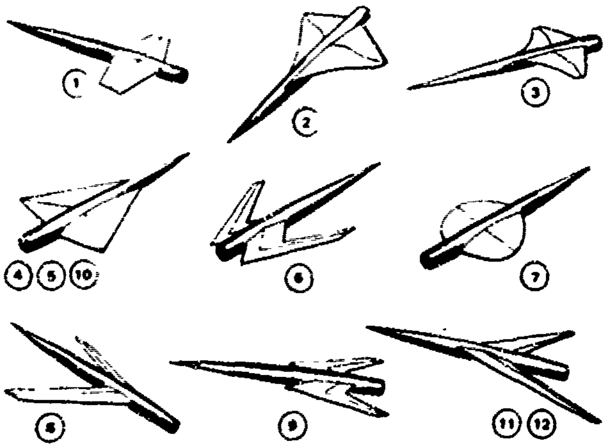
This paper treats topics in the areas of sonic boom operation, propagation, and minimization. Only the discussion concerning sonic boom minimization is summarized here.

The sonic boom minimization concept discussed is that of redistributing the variation of an aircraft's pressure field around the Mach cone to reduce the overpressure directly below practical aircraft configurations. The utility of this idea is based on two factors affecting the propagation of disturbances in different azimuthal planes: (1) disturbance in other than the vertical plane will travel a longer distance before intercepting the ground and will thus have decayed somewhat more; and (2) lateral cutoff due to atmospheric refraction. It is proposed that multipole effects be used to accomplish this pressure redistribution. The discussion concerning the use of such multipole effects is a summary of that presented in early papers (see capsule summaries M-23 and M-19). The reader is referred to the capsule summaries of those papers for further details.

M-31
CURRENT RESEARCH IN SONIC BOOM
Lynn W. Hunton
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 57-66

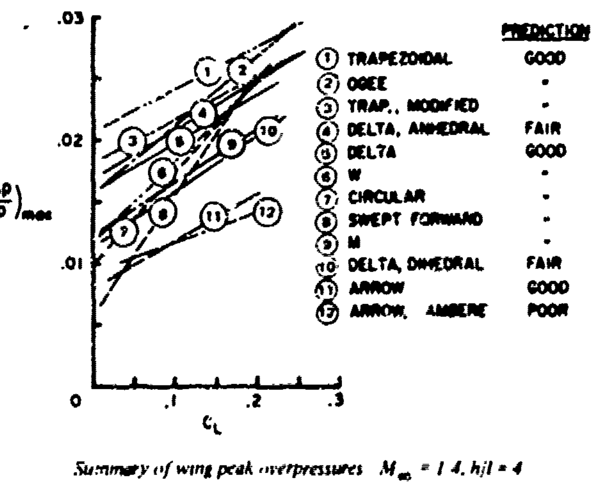
This paper reviews the sonic boom research conducted at NASA Ames Research Center during the year previous to this conference. Only the portion of the paper dealing with boom minimization concepts will be summarized here. The rest of the paper is summarized in capsule summary G-40.

The boom minimization program described here consisted of a wind tunnel study of wing configurations having various planforms, dihedrals, and cambers. These included trapezoidal planforms, circular planforms, delta planforms, swept forward planforms, arrow planforms, ogee planforms, "W" planforms, and "M" planforms, as shown in the figure below, which was taken from this paper. The geometric parameters held constant included: the body with a parabolic arc mass and a length of 7 inches, the total wetted area, the wing span, the exposed aspect ratio, and the wing thickness consisting of a double-wedge section with a maximum thickness ratio of 5 percent. The one exception to these conditions was the circular wing which, in order to satisfy the wetted area requirement, had a smaller span and hence a lower aspect ratio.



Study configurations

A summary of the preliminary overpressure characteristics measured for these various wings in the presence of a fixed body is given in the figure below, which was taken from this paper. Also shown is a table on the right which summarizes in somewhat gross terms the measure of success with which the characteristics of these wings could be predicted by theory.



Summary of wing peak overpressures $M_\infty = 1.4$, $h/l = 4$

The following conclusions were reached as a result of these measurements:

1. A relatively large spread in overpressures was obtained for this series of wings ranging from the unswept trapezoidal down to the highly sweptback arrow and the limits of this spread were predicted by theory.

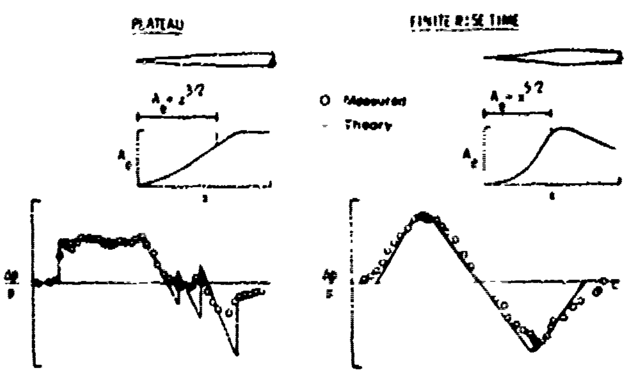
2. Camber for the arrow wing was advantageous at the higher lift coefficients.

3. The variation in lift effectiveness on the overpressure as evidenced by the differences in the shapes of the curves is quite large and preliminary estimates of these effects were generally successful. However, some problems arose in the case of the cambered arrow wing.

4. Wing dihedral on the delta configuration showed a surprisingly large effect on the overpressure.

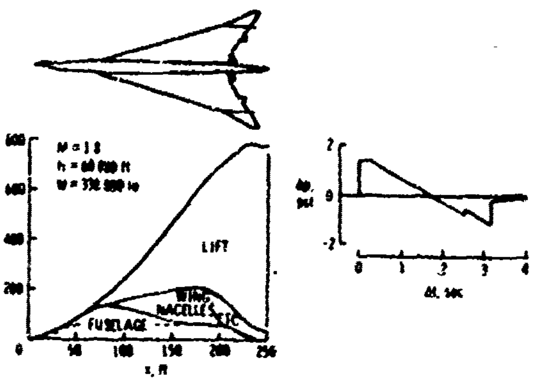
M-32
CONFIGURATION DESIGN FOR SPECIFIED PRESSURE SIGNATURE CHARACTERISTICS
F. Edward McLean
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 37-45

This paper presents design requirements for the plateau pressure signature and the signature with finite rise time. Such signatures can be obtained through the use of near-field design concept. It is shown that the plateau signature shape is generated by an effective area development that varies as the three-halves power of the distance along the axis. Such a signature, as shown on the left side of the figure below, which was taken from this paper, is characterized by a constant pressure region behind the bow shock. For airplane operating conditions where it is possible to generate this type of signature on the ground, the total pressure rise in the disturbance would be somewhat less than that of the corresponding far-field N-wave. A pressure signature with a finite rise time is illustrated on the right of the figure below. This signature is generated by an effective area distribution which varies as the five-halves power of distance along the axis, to about the midpoint of the body length. Aft of the body midpoint, the area development is a much more complicated variation with distance along the axis. The experimental pressure signatures, represented by the circles, were measured in the flow fields of bodies of revolution with the required area developments.



Near-field pressure signatures

A domestic SST configuration was then designed so as to produce a plateau-type pressure signature. At the design Mach number (M = 1.8), the volume and lift elements of the airplane were carefully tailored to provide a three-halves power effective area distribution for the assumed altitude of 60,000 feet and airplane weight of 338,000 pounds. The resulting configuration and theoretical pressure signature are shown in the figure below, which was taken from this paper.



Use of plateau signature in domestic SST study

In order to produce a finite rise time signature, it is shown that the required length is extremely large. For example, to provide a rise time of 10 to 15 milliseconds at the ground for an airplane weighing 600,000 pounds, an effective length of approximately 1,000 feet would be required. Use of electrostatic effects or laser beams to increase the effective length of the airplane are discussed briefly, but it is concluded that the required power is prohibitively large.

McLean and Shrout also discussed the use of near-field effects to reduce sonic boom overpressure in an earlier paper (see capsule summary M-11). The airplane configuration discussed in the present paper which produces a plateau pressure signature was also discussed in the earlier paper. As pointed out in the capsule summary of the earlier paper, the development of near-field boom minimization concepts was an important stimulus to sonic boom minimization efforts.

M-33
THE APPROACH TO FAR-FIELD SONIC BOOM
F. K. Moore and L. F. Henderson
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 107-115

In this paper a series is derived which describes small departures from an N-wave for bodies of smooth and discontinuous slope. The purpose is to restrict attention to the approach to far-field and thereby obtain a simpler way to relate signature improvements to the aircraft configuration. It is assumed that the observed signature would be nearly an N-wave and Whitham's theory is used to describe the first departure from that result as one moves toward the body.

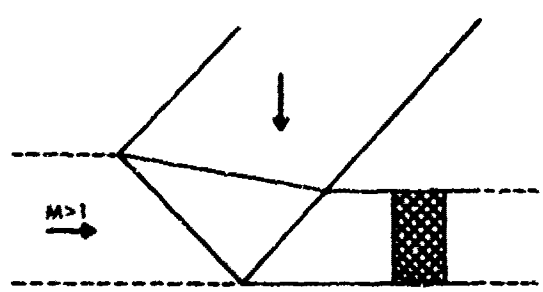
Whitham's non-asymptotic formula (see capsule summary G-3) for the bow shock overpressure is expanded in terms of a small parameter ϵ, which depends upon the F-function of the body. An Euler transformation is found to improve the convergence of the series. The series is used to determine how changes in the equivalent body shape can modify the signature in the region of approach to the far-field.

It is found that the addition of a compression ahead of an expansion corner decreases the bow shock overpressure, not everywhere in the flow, but as the N-wave is approached. It is also found that no modification is possible for smooth bodies which will favorably affect the nearly far-field shock strength.

In a later paper (see capsule summary M-55) Henderson extends the theory developed here.

M-34
REDUCTION OF SONIC BOOM ATTRIBUTED TO LIFT
E. L. Resler, Jr.
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 99-106

This paper contains a discussion of a wing configuration which would eliminate completely the boom attributed to lift. This configuration consists of a flat plate at angle of attack with another horizontal flat plate below it to intercept the downward directed waves (see figure below). Thus lift is produced only by suction on the upper side. In order to maintain a horizontal streamline, the air in the streamtube between the plates must be processed to prevent "pluming" of the streamtube as it leaves the duct, which would cause a boom. The possibility of using the engines to accomplish this processing is then investigated. It is found that only a limited area reduction between the upper and lower surfaces of the wing between the front edge and rear edge is possible, limiting the magnitude of the lift contribution to the boom that could be offset by this method.



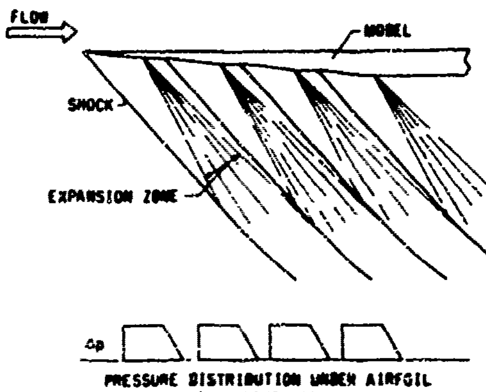
Two dimensional lifting configuration with no sonic boom

In an earlier paper (see capsule summary UC-1) Resler showed that if the air flow between the two wing surfaces is not "processed" the wing will have no lift.

M-35
EVALUATION OF CERTAIN MINIMUM BOOM CONCEPTS
Harry L. Runyan and Harbert R. Henderson
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 47-55

This paper deals with two topics. The first is the development of three dimensional flow with increasing distance from a two-dimensional body and its effect on two-dimensional sonic boom minimization schemes. The second is the development of a sonic boom efficiency factor so that various configurations can be systematically compared.

The three-dimensional effects were investigated by constructing a two-dimensional airfoil with a stepped bottom surface, as shown in the figure below, which was taken from this paper. Calculations showed that such a model would produce a stepped pressure distribution. This two-dimensional pressure distribution was u d as an input to a computer program to calculate an pressure on the ground through a standard but stratified atmosphere, and the resulting ΔP was one-fourth psf. The model was then tested in a wind tunnel, and the pressure distribution measured at a distance of five body lengths was used as input to the same computer program, resulting in a ground pressure of 2.5 psf. It is concluded that this illustrates the danger of deriving shockless or minimum boom configurations based on two-dimensional flow fields.



Conceptual model for shock cancellation technique based on two-dimensional flow

The following sonic boom efficiency factor is then proposed:

$$\frac{L}{D\left(\frac{\Delta P}{P}\right)} \quad \text{where } L = \text{lift}, \quad D = \text{drag}$$

and $\left(\frac{\Delta P}{P}\right)$ refers to the maximum overpressure on the ground.

The reasoning behind this factor is that factors other than low boom must be considered in evaluating a supersonic transport concept, and one of the more important is the lift-drag ratio, because the range and efficiency of the aircraft are highly dependent on this ratio. This factor is then evaluated for three different configurations having rectangular, delta, and arrow planforms. It was found that the planform having the highest efficiency of those studied was the 70° arrow wing of aspect ratio 20, at an angle of attack of 1°, which had a factor of 186,000 as well as having the lowest ΔP of 0.67 psf. The lowest efficiency factor was that of the delta wing. It was felt by the authors that the structural aspects of these configurations should be studied and a more complete efficiency factor formulated that would include structural weight

In another paper (see capsule summary M-51) Runyan, et al also investigated the development of three-dimensional effects of a two-dimensional airfoil.

M-36
GENERAL REMARKS ON SONIC BOOM
A. R. Seebass
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 175-179

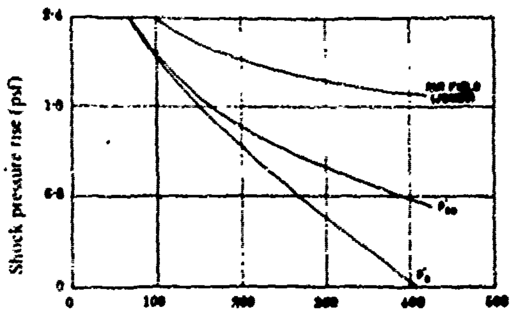
This is a brief review of the state of the art of sonic boom minimization as of 1968. Topics touched upon are: (1) sonic boom reduction through improved overall airplane efficiency, such as improvements in lift-to-drag and engine thrust-to-weight ratios, as well as in structural weight and specific fuel consumption; (2) utilization of interference effects to eliminate the volume contribution to the sonic boom; (3) configuration modifications approach the far-field lower bound for the overpressure; (4) reduction of sonic boom due to lift by a reduction in engine stream tube area; (5) and the design of aircraft to produce finite rise-time pressure signatures. Only the last topic is discussed in any depth. It is shown that when the effects of non-uniform atmosphere are taken into account, McLean's results (see capsule summary M-32) for the airplane length required to produce a finite rise-time signature are too pessimistic. The lengths found here are about 30% less for an airplane altitude of 60,000 feet than those found by McLean. These lengths are still much too long for practical configurations, however. It is tentatively concluded that major gains in sonic boom reduction may be expected in the future from improvements in the overall efficiency of SST-type aircraft, as well as through novel design features, and that such gains may be sufficient to allow commercial supersonic flights over populated areas.

This discussion gives a good brief overview of the prospects for significant sonic boom reduction as of 1968.

M-37
MINIMUM SONIC BOOM SHOCK STRENGTHS AND OVERPRESSURES
R. Seebass
Nature, Vol. 221, No. 5181, Feb. 15, 1969, pp. 651-653

This paper presents formulae that give the minimum achievable shock pressure and the minimum achievable overpressure level, for given aircraft and flight conditions. The results are for an isothermal atmosphere. Near field effects are taken into account.

It is pointed out that for any given aircraft weight, flight Mach number, and altitude, shock waves may be avoided altogether. This is a result of near-field effects and the "freezing effect" (see capsule summary P-98) of the atmosphere. The two equations derived in this paper for the minimum shock pressure P'_s and minimum achievable overpressure level P'_{s_o} were used to develop the figure below. This figure shows the minimum front shock wave pressure rise and overpressure as a function of aircraft length for a 600,000 pound aircraft flying at a Mach number of 2.7 at 60,000 feet. Also indicated on the figure is the far-field lower bound of Jones (see capsule summary M-6). The gains over the far-field lower bound are due to near-field effects.



Minimum front shock pressure rise P_S' and overpressure P'_{s_0} as a function of length for the following conditions: $W = 600{,}000$ lbs; $M = 2.7$, $h = 60{,}000$ ft

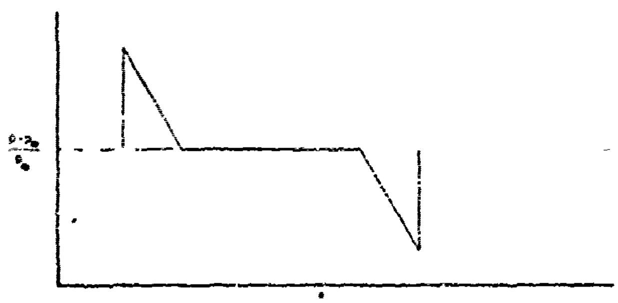
Equations are also given for calculating the minimum shock pressure and overpressure when both the front and rear shock pressure rises are minimized simultaneously. The gains over the far-field lower bound are not as large for this case.

It is stated that there seems to be no reason why aircraft cannot be designed to approach these lower bounds without incurring excessive performance penalties. However, no calculations are made to substantiate this statement.

M-38

INVESTIGATION OF A CLASS OF BODIES THAT GENERATES FAR-FIELD SONIC BOOM SHOCK STRENGTH AND IMPULSE INDEPENDENT OF BODY LENGTH AND VOLUME
Raymond L. Barger and Frank L. Jordan, Jr.
NASA TND-5148, May 1969

A study of a design method which provides a means of continually increasing the volume of a body without increasing the maximum impulse or overpressure is presented in this report. The method is based upon designing the body so that its pressure signature has a region of zero overpressure between the positive portion of the signature and the negative portion of the signature, as shown in the figure below.



Modified N-wave signature

In an earlier paper (see capsule summary M-25) Barger derived a procedure for deriving the shape of a body that will produce such a signature.

This procedure was used in the present study in conjunction with the design of three models. The ratios of the lengths of models B and C to model A were 2.5 and 4, respectively. The ratios of the volumes of models B and C to that of model A are 7.6 and 16.6, respectively. The shapes for the three models were designed to produce pressure signatures having the following properties. The signatures generated by models B and C were to have the same magnitudes of maximum overpressure and impulse in their initial positive sections as the signature generated by model A. Further, the signature generated by model A was to have no region of zero overpressure between the initial positive and succeeding negative lobes, whereas the signatures generated by model B and model C were to have progressively longer regions of zero overpressure.

Calculated and wind-tunnel-measured signatures for each of the three bodies at distances of 38 cm and 84 cm showed the following: (1) the calculated and experimental signatures were in reasonable good agreement; (2) at the 38-cm station (in terms of body lengths this distance represents 7.5, 3, and 1.88 lengths, respectively) the bow shock overpressures were within 7 percent of their average value, whereas at the 94-cm station (this represents 18.5, 7.4, and 4.63 body lengths, respectively) they were within 4 percent of the average; and (3) the values of the impulse of the front portion of the shock were within 5 percent of their average value at the 38-cm station and within 4 percent of the average at the 94-cm station.

It is concluded that it is possible to modify the shape of a body that produces acceptable far-field sonic boom characteristics so as to increase the volume of the body significantly without increasing the far-field overpressure or impulse.

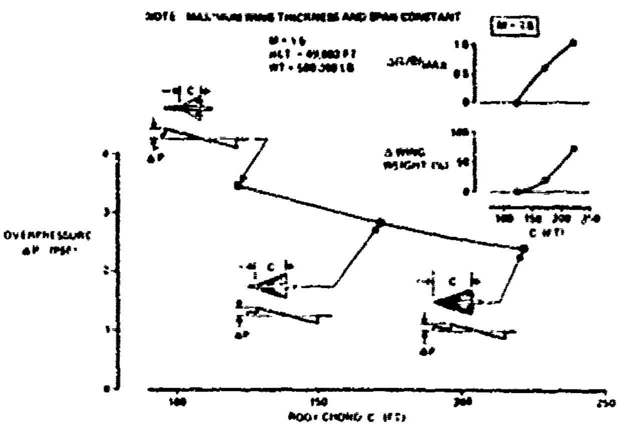
In a paper by Howell, Sigalla, and Kane (see capsule summary M-39) it was shown that increased volume could be used to offset some of the sonic boom due to lift. It was also shown that this resulted in an excessive drag increase. Since, for most flight conditions, the sonic boom of a typical SST configuration is lift-dominated, the findings of the present paper concerning volume effects are of limited utility.

M-39

SONIC BOOM CONSIDERATIONS IN AIRCRAFT DESIGN
Clarence S. Howell, Armand Sigalla, and Edward J. Kane
AGARD Conference Proceedings No. 42, Aircraft Engine Noise and Sonic Boom, May 1969, pp. 30-1 thru 30-7

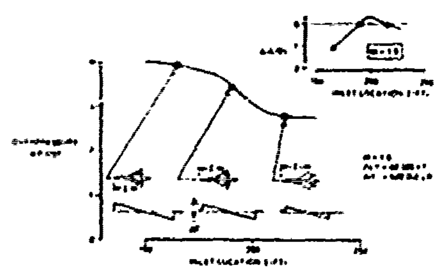
The purpose of this paper is to assess the known aerodynamic design methods for minimizing and modifying a sonic boom signature. The corresponding effects on aerodynamic efficiency (lift-drag ratio) are shown to illustrate the resulting performance compromise. Mach number, altitude, and gross weight representative of a large supersonic commercial or military airplane during climb and acceleration are used for comparative purposes.

It is shown that nozzle area, thrust vectoring, wing camber and twist, and forebody lift can, through proper design, have a beneficial effect on the sonic boom. These effects are very small, however. It is also shown that significant reductions in the sonic boom intensity can be achieved by stretching the wing length and volume and by locating the engines as far aft as possible. These last two findings are illustrated in the figures below, along with the effect that such modifications have on the airplane drag. From the first figure it can be seen that both reduced sonic boom and increased supersonic aerodynamic



Effect of stretching wing lift and volume

efficiency favor very slender planforms, in practice, slenderness is limited by structural weight and other design considerations. The second figure shows that if the engines are far enough aft, their shock wave is prevented from reinforcing that of the wing leading edge and that of the body. It is pointed out, however, that practical considerations suggest that the most rearward position of the engines be dictated by drag and structural feasibility rather than by sonic boom.



Effect of engine location

The use of increased body volume to decrease sonic boom intensity through interference effects is shown to result in excessive drag increases. However, fuselage "area ruling" can make a considerable reduction in drag without aggravating the sonic boom.

The effect of the "phantom" forebody, where the airplane is virtually lengthened through electrostatic fields or other electrical and magnetic phenomena, is shown to be negligible despite an enormous electrical power consumption. It is also shown that, in order for the pressure signature to have a finite rise time, very large airplane lengths are required.

The coverage in this paper of the effects of configuration variables on sonic boom intensity is broader than that of any previous paper.

M-40
EFFECTS OF LENGTHWISE LIFT DISTRIBUTION ON SONIC BOOM OF SST CONFIGURATIONS
Antonio Ferri and Ahmed Ismail
AIAA Journal, Vol. 7, No. 8, August 1969, pp. 1538-1341

This paper is a condensed version of an earlier report. The reader is referred to capsule summary M-24 for details.

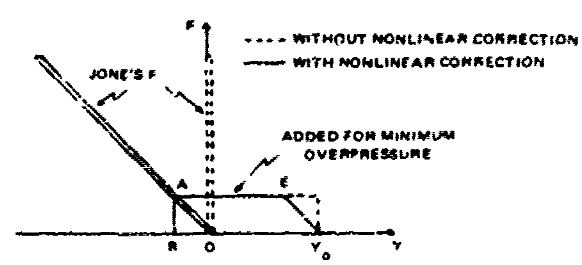
M-41
LOWER BOUNDS FOR SONIC BOOMS IN THE MIDFIELD
A. R. George
AIAA Journal, Vol. 7, No. 8, August 1969, pp. 1542-1545

This paper presents lower bounds for sonic booms based on minimizing either the overpressure or the shock strength of the positive part of the signature. The results are not restricted to the limit of large distance from the aircraft. They reduce to the Jones lower bound infinitely far from the aircraft in a uniform atmosphere, but they give reductions from the Jones lower bound of the order of 50% for planned supersonic transport conditions. This is because the asymptotic results of Jones are approached very slowly (as $r^{-1/4}$) in a uniform atmosphere and are never reached in the real atmosphere.

The analysis was focused upon lift, since in most cases total lift is the limiting factor. The minimization procedure starts with the F-curve (see capsule summary G-3) for the Jones far-field lower bound (see capsule summary M-6). This F-curve has the form of a delta function at y = 0, (where y is distance from the nose of the airplane) illustrated approximately by the dashed line of the figure below. The tilted curve has been advanced to account for nonlinear effects (see capsule summary P-92). The additional area AEy_oO can be added to the original delta function without additional overpressure (see capsule summary G-3 for an explanation of the technique for locating shocks in a multivalued signature), since the triangular area AOB balances essentially the whole positive area

$$\int_0^{y_o} F(y)dy.$$

As Jones has shown (see capsule summary M-6), the lift or volume is given by integrals of the positive part of F multiplied by a positive weighting function. Thus for a given lift or volume, the additional area AEy_oO allows reduction of the area in the delta function and a resulting reduction in the shock strength AB. In the limit in a uniform atmosphere the additional area is negligible compared to that in the delta function and the result reduces to that of Jones.



Overpressure lower bound, with and without nonlinear correction

An additional area is then added to the F-curve in order to give the pressure curve a finite rise time. This addition also results in a reduction

of the area in the delta function. Thus the total F is given by $F = F_1 + F_2$ for the overpressure minimum and by $F = F_1 + F_2 + F_3$ for the shock strength lower bound, where $F_1(\eta) = K\delta(\eta)$, $F_2(\eta) = C$, and $F_3(\eta) = D\eta$, where $\delta(\eta)$ is the Dirac delta function and K, C, and D are constants chosen so that the advanced wave will be the optimum and produce the required lift. It is shown that C must be chosen so that the overpressure Δp due to F_2 will just equal the shock strength ΔP. Equations are then derived for all three constants.

Some numerical examples are considered which show that the shock strength and lower bounds of the present paper are significantly lower than those obtained by Jones and Ferri (see capsule summary M-24). However, the Jones far-field optimum still gives the minimum positive impulse for all altitudes. The present results give impulses typically 30-50% higher than those of Jones.

This analysis treats only the front half of the wave. Although the rear shock and negative overpressure of a lifting configuration are usually less than the corresponding values for the front of the wave, the present analysis' large reduction in the front means that the tail wave will have to be modified to reduce its strength to a level comparable to that of the front wave. The authors conclude that this will reduce the effective length available for front wave minimization.

It is pointed out by the authors that these minimums must be interpreted as idealizations, which can only be approached by real aircraft designs. However, the required curves are less singular than the Jones results and thus can undoubtedly be more closely approached for given drag and configuration limitations.

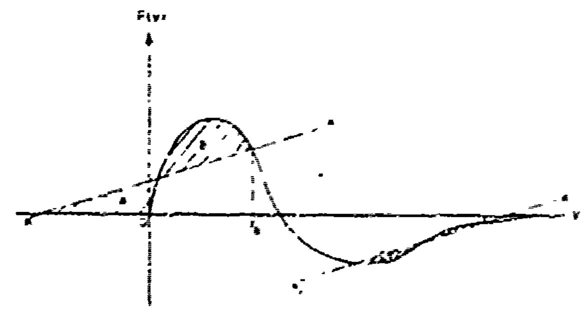
M-42
LOWER BOUNDS FOR THE PRESSURE JUMP OF THE BOW SHOCK OF A SUPERSONIC TRANSPORT
L. B. Jones
The Aeronautical Quarterly, Vol. XXI, February 1970, pp. 1-17

A preliminary study is presented in this paper of the effect of minimizing the pressure jump across the shock waves of a body, as evaluated using Whitham's non-asymptotic formula (see capsule summary G-3). The shock waves of a slender aircraft are considered at a great distance from the aircraft so that all the shocks have coalesced into either the bow or rear shocks, but not at such a great distance (asymptotic) that the two shocks are of equal strength. Lower bounds are determined for the pressure jump across the bow shock subject to various aircraft constraints, and the pressure jumps across both the bow and rear shocks are determined at off-design conditions.

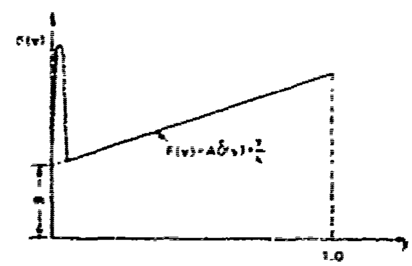
The method used here is very similar to that used by Jones in an earlier paper (see capsule summary M-16). However, in the previous paper the problem involved finding the minimum of

$$\int_0^{y_c} F(\eta)d\eta \quad \text{given certain constraints on}$$

$F(\eta)$ ($F(\eta)$ is the Whitham F-function defined in capsule summary G-3), since the asymptotic lower bound was what was wanted. In the present paper the problem of determining the minimum value of ΔP for the bow shock becomes the problem of determining the minimum value of $F(y_B)$ subject to constraints on the F-function involving weight, volume, base area, etc. Here y_B is determined, as shown in the first figure below, using Whitham's "area balancing" technique (see capsule summary G-3). The resulting F-function for the lower bound values of the pressure jump of the bow shock is shown in the second figure below.



Definition of y_B



F-function for the lower bound values of the pressure jump of the bow shock

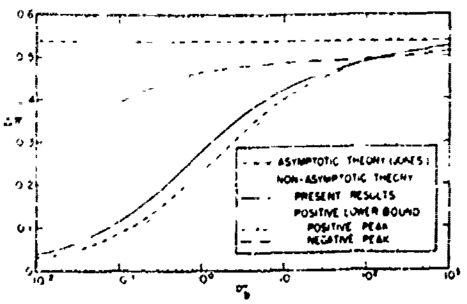
After determining the ratio of the non-asymptotic lower bound bow shock to the asymptotic bow shock lower bound for various design conditions, the pressure jump across the bow and rear shocks at off design conditions is determined. The results show that it is necessary to choose the design case with some care. In some cases a minimum value of the pressure jump across the bow shock at the design condition can lead to high values of the pressure jump across the rear shock and for the bow shock at off-design conditions. In other cases, designing for a minimum value at a particular design condition can lead to low values for the pressure jump across both bow and rear shocks over the whole supersonic flight path.

George (see capsule summary M-41) made a similar investigation into the nonasymptotic lower bounds for the bow shock strength. He obtained an optimum form for the F-function very similar to the one found in the present paper.

M-43
LOWER BOUNDS FOR SONIC BOOM CONSIDERING THE NEGATIVE OVERPRESSURE REGION
James S. Petty
Journal of Aircraft, Vol. 7, No. 4, July-August 1970, pp. 375-377

This paper presents an investigation of the lower bounds for sonic boom overpressure considering both the positive and negative overpressure regions. Whitham's general (nonasymptotic) theory

(see capsule summary G-3) is used to derive the F-function which gives the lower bound peak positive overpressure subject to the requirement that the magnitude of the rear shock wave must not be greater than the front shock intensity. The strength of the aft shock is determined by assuming that for $\chi > \ell$, where χ is the distance along body axis from nose and ℓ is the body length, the equivalent area distribution $A_e(\chi) = A_e(\ell) \equiv A_{e,b}$. The resulting F-function is such that the positive area under F(y) is concentrated near y = 0 and the negative area near y = ℓ.
Using the relations derived for the rear shock from Whitham's general theory, together with the expression for the F-function, the relation between a nondimensionalized expression, $\Delta\pi$, related to the peak overpressure and a nondimensionalized expression, σ_b, related to $A_{e,b}$ is derived. The figure below, which was taken from this paper, shows the nondimensional peak overpressure magnitude $\Delta\pi$ for the present lower bound solution. Also shown is the asymptotic lower bound solution of Jones (see capsule summary M-16) and the solution for the lower bound peak overpressure (not considering negative overpressure region). For the latter case, the peak negative overpressure magnitude is also shown, and can be seen to be much higher than the positive overpressure. The figure shows that consideration of both positive and negative overpressures results in a large decrease in peak negative overpressure magnitude with a relatively small penalty in peak positive overpressure.



Peak overpressure magnitudes from several lower bound analyses

In earlier papers George (see capsule summary M-41) and Jones (see capsule summary M-42) investigated the lower bound of positive overpressure in the mid-field, but no constraints were put on the rear shock overpressure. The present paper was the first to consider both the positive and negative overpressure regions.

M-44
PRACTICAL ASPECTS OF SONIC BOOM PROBLEMS
Antonio Ferri and Lu Ting
ICAS Paper No. 70-23, The Seventh Congress of the International Council of the Aeronautical Sciences, Consiglio Nazionale Delle Ricerche, Roma, Italy, September 14-18, 1970

In this paper SST configurations selected from the point of minimizing sonic booms are investigated. The parameters investigated here are weight of the airplane configuration, length, Mach number, and altitude of flight. Details of the signature are related directly to the airplane configuration. The results were derived using two different numerical programs: (1) that of Carlson (see capsule summary G-23); and (2) that of Hayes (see capsule summary P-98).

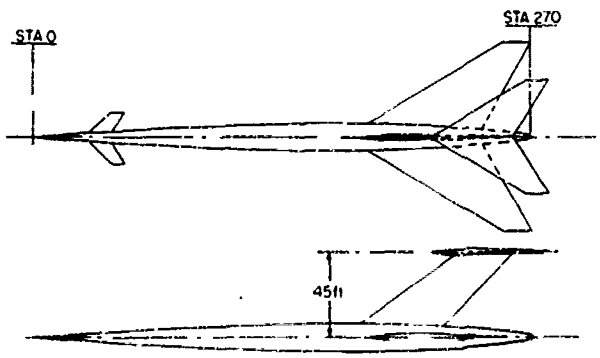
The results of the analysis indicate the following:

1. A minimum concentration of equivalent cross sectional area is required in the front portion of the configuration in order to obtain near-field effects. Such a minimum depends on the Mach number and altitude of flight. However, the details of such a distribution are not too important provided that the distribution is not too different from the optimum shape.

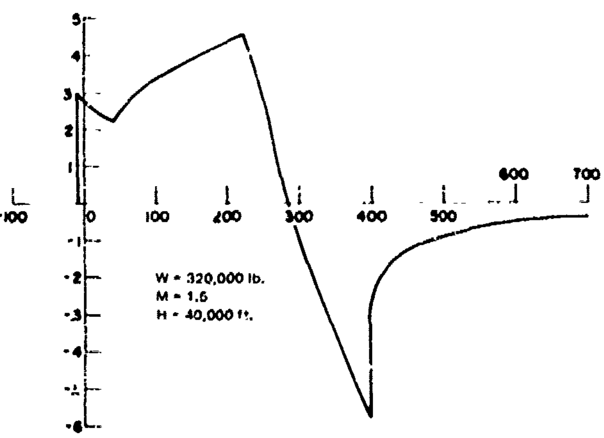
2. An increase of length permits decreasing somewhat the ΔP_{max} and permits having a slender fuselage.

3. The required length of the airplane can be exchanged with the height of the lifting surfaces of the airplane. This possibility suggests that a biplane having wings that do not interfere at supersonic speeds, and do not choke at transonic speeds, has some good possibilities from the point of view of reducing sonic boom. It is possible to reduce the jump in ΔP due to the sonic boom for an airplane 460,000 pounds flying at 60,000 feet and M = 2.7 to values of the order of 0.5 to 0.6.

4. Values as low as 0.4 to 0.5 psf for the bow shock overpressure are possible using a biplane configuration when the weight is reduced to 320,000 pounds for cross-country operations. The proposed configuration and its pressure signature are shown in the figures below.



Proposed configuration



Pressure signature of biplane configuration with a length of 300 ft, height of 45 ft

It can be seen from the second figure that the trailing shock does not decrease in the same proportion as the front shock. However, the overpressure of the rear shock is still less than 0.6 psf.

This paper presents only a brief analysis of the effects of the proposed configuration modifications on aircraft performance.

M-45

APPLICATION OF MULTIVARIABLE SEARCH TECHNIQUES TO THE DESIGN OF LOW SONIC BOOM OVERPRESSURE BODY SHAPES

D. S. Hague and R. T. Jones

NASA CR-73496   vember 1970

In this r   a variety of sonic boom minimization prob.   are investigated by multivariable search techniques. The general nonlinear multivariable optimization problem is concerned with the maximization or minimization of a payoff or performance function of the form

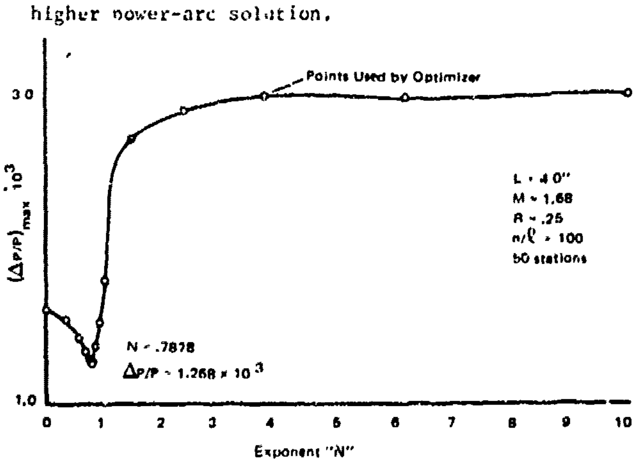
$$\phi = \phi(\alpha_i), \; i = 1,2, \; . \; . \; . \; N$$

subject to an array of constraints

$$C_j = C_j(\alpha_i) = 0, \; j=1,2, \; . \; . \; . \; . \; , \; P$$

The α_i are the independent variables whose values are to be determined so as to maximize or minimize ϕ subject to the constraints.

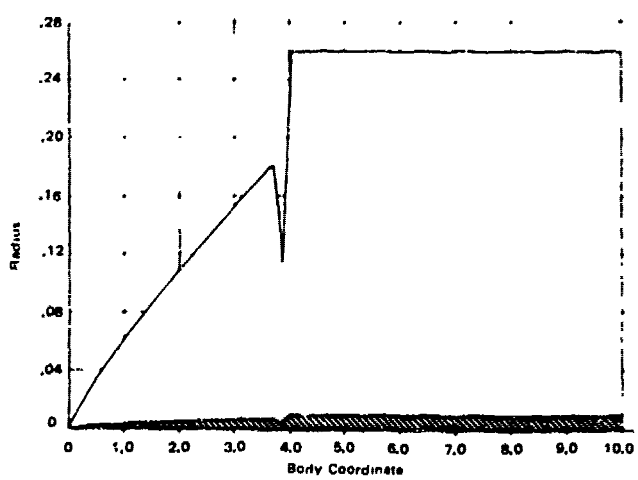
The most elementary problems studied are those involving a single power arc. Single power body shapes are defined as those body shapes described by a radius distribution r(x) of the form $r(x) = cx^N$. In these problems geometric constraints are applied to reduce the optimization to one involving a single parameter. The problem simplicity permits the construction of charts illustrating the variation of sonic boom overpressure over a wide range of Mach numbers and distances from the body axes. The charts and optimization studies reveal that close to the body a three-quarter power shape will provide the lowest overpressure. Deviations from this exponent result in rapid increase in overpressure, as shown in the figure below, which was taken from this paper. As distance from the body axis increases, an unsensitive extremal shape appears at gradually decreasing values of the power body exponent. With this class of bodies an increase in Mach number, base radius, or volume all tend to drive the solution toward the more sensitive higher power-arc solution.



Variation of maximum overpressure with power body exponent with radius and length constrained

Next in order of complexity above the single-power arc solutions are those involving two-power arcs with a slope discontinuity at the junction between the two arcs. In general, the two-arc solutions obtained fail to produce a minimum-maximum overpressure significantly below that of the single-power arc body subject to the same physical conditions and geometric constraints. The total impulse of the pressure signature is well below that of the corresponding single-power solution, however.

The problems next in order of complexity dealt with are the three-power arc bodies involving seven free parameters. Body shapes of this type produce a significant reduction in minimum-maximum overpressure when compared to the corresponding single-arc solution. In all cases considered the overpressure is reduced by approximately one-third. The optimal three-arc body is shown in the figure below. The lower overpressure is obtained by the device of a conventional forebody of reduced base area followed by a notch creating strong self-cancelling positive and negative pressure waves. The notch walls are ideally sonic; however, it is shown that a moderate reduction in slope is possible without significant increase in overpressure. The notch ideally occupies a small portion of the body length. Again, it is shown that the notch width can be increased for a small increase in overpressure. When the body shape is viewed as an equivalent body of revolution, it is shown that the first two arcs would physically represent body volume, and the third arc would physically represent wing lift. Such a configuration would imply a relatively unswept canard configuration.



Optimal three-arc body

The most general otpimization problem considered in the investigation is that of shaping an arbitrary body of revolution. While the resulting shapes possess low sonic boom overpressure, their irregularity appear to prohibit their use in an aircraft configuration unless the low boom property can be maintained while imposing some reasonable smoothness criteria. This was not achieved within this study.

M-46

ON SHOCK IMPEDANCE

L. F. Henderson

J. Fluid Mech., Vol. 40, Part 4, 1970, pp. 719-735

An expression for shock impedance is derived in this paper and is subjected to a fairly searching study. The portion of the paper dealing with sonic booms concerns the use of impedance mismatch to reduce the sonic boom overpressure. It is suggested that one way this might be done is to make use of the impedance of the propelling jets. It would be necessary to place the engines underneath the aircraft in such a way that the jets intercept as much of the signature as possible. Then with the jet Mach number Mj→1, and with the jets made as hot as possible, say by the use of afterburners, the condition may be reached where the signature waves reflect off the top edges of the jets instead of refracting through them. Inside the jets, precursor and postcursor waves will exist, and the jets act as a kind of waveguide for these unsteady waves. These waves will themselves make disturbances at the bottom edges of the jets and this in turn will cause waves to be propagated towards the ground. If such a wave system were able to propagate far enough it would eventually organize itself into a somewhat unsteady N-wave. It is concluded that the ultimate effect of the impedance mismatch is to cause the aircraft to appear longer in the far-field, so the overpressure is reduced by forcing the signature to be more spread out.

The concept discussed here was treated very briefly. In order to evaluate its feasibility a much more thorough analysis would have to be made.

M-47
SOME NOTES ON THE PRESENT STATUS OF SONIC BOOM PREDICTION AND MINIMIZATION RESEARCH
Harry W. Carlson
NASA SP-255, Third Conference on Sonic Boom Research, 1970, pp. 395-399

A brief, general discussion of minimization, propagation, and generation concepts is presented in this paper. Only the minimization concepts discussed will be summarized here.

The main idea stressed is that the problem of sonic boom minimization through airplane shaping is inseparable from the problems of optimization of aerodynamic efficiency, propulsion efficiency, and structural weight. Substantial improvement in any of these factors would have a direct beneficial influence on sonic boom minimization. Airplane shaping based on sonic boom considerations alone, however, does not necessarily bring about improvement in the other factors.

It is also pointed out that there is a need for improved understanding of hypersonic boom phenomena and a need for the development of prediction and minimization techniques in this speed range.

M-48
APPLICATION OF MULTIVARIABLE SEARCH TECHNIQUES TO THE DESIGN OF LOW SONIC BOOM OVERPRESSURE BODY SHAPES
D. S. Hague and R. T. Jones
NASA SP-255, Third Conference on Sonic Boom Research, 1970, pp. 307-323

This is a condensed version of NASA CR-73496 (see capsule summary M-45). The reader is referred to the capsule summary of that report for details of this work.

M-49
THEORETICAL PROBLEMS RELATED TO SONIC BOOM
W. D. Hayes, J. H. Gardner, D. A. Caughey, and F. B. Weiskopf, Jr.
NASA SP-255, Third Conference on Sonic Boom Research, Oct. 29-30, 1970, pp. 27-31

This paper is a brief report of research that was in progress at Princeton University on problems of wave propegation and sonic boom at the time this conference was held. Most of this research dealt with sonic boom propagation. However, a discussion of bangless boom optimums is also presented, and it is this portion of the paper that is summarized here. For a discussion of the other topics covered in this paper, the reader is referred to capsule summary P-140.

The problem considered is this: For an aircraft of specified effective length at a high altitude, determine the maximum gross weight that causes no (or rather an incipient) shock wave on the ground. This is done by relating the weight of the airplane, the F-function, and the age variable, since for no shock to appear in the final signature, the maximum slope of the F-function must be less than the inverse of the corresponding age variable.

Simplifying assumptions are used to obtain an equation giving the maximum permissible gross weight of the aircraft. It is assumed that the aircraft is in uniform level flight at a high altitude, and the ray immediately beneath the aircraft is considered. The appropriate age is that corresponding to an altitude difference of $\pi/2$ times the scale height $a^2/\gamma g$ at the aircraft altitude. The two principal implications of the resulting equation are: (1) The aircraft must not fly too high; the results for 30,000 feet appear reasonable and attainable, while those for 60,000 feet are out of reasonable range; (2) The aircraft effective length must, by careful design, be made as large as possible. If the aircraft is to fly at a high Mach number, there must be a vertical distribution of aerodynamic components, with some components located low and forward and others high and aft.

McLean (see capsule summary M-32) also investigated airplane configurations which would produce finite rise time pressure signatures. He also reached the conclusion that extremely large lengths would be required.

Hayes and Weiskopf present a much more extensive discussion of bangless sonic boom optimums in the paper summarized in capsule summary M-60.

M-50
COMMENTS ON LOW SONIC BOOM CONFIGURATION RESEARCH
Lynn W. Hunton
NASA SP-255, Third Conference on Sonic Boom Research, 1970, pp. 415-419

A brief comment on basic design problems encountered in transforming an optimum area distribution for low boom into an equivalent lifting airplane configuration is presented in this paper. The two main problems discussed are the need for accurate calculation of the vehicle lift distribution and the decreasing accuracy of Whitham's theory above $M = 2$ (see capsule summary G-54).

The overpressure characteristics for low boom configuration concepts are generally quite sensitive to small deviations in the equivalent area distribution.

Since the lift at cruise represents about 50 to 70 percent of the equivalent cross-sectional area of the vehicle for sonic boom calculation purposes, small changes in the lift distribution due to either design changes or problems of accuracy in the theory can lead to significant effects in the final overpressure results. It is pointed out that the more sophisticated methods available for calculating loads on wing-body combinations at supersonic speed do provide quite accurate estimates of gross lift effects, such as the lift curve slope, but these methods do not yield accurate predictions of center of pressure at the higher Mach numbers.

Due to the decrease in accuracy of Whitham's theory above $M = 2$, it is concluded that it will only provide a preliminary guide to the overpressure characteristics for lifting configurations at Mach numbers greater than about 2. Until such time as ongoing studies produce improved analytical methods for the $M>2$ case, it is concluded that near-field measurements in the wind tunnel will provide the most reliable basis for the prediction of the overpressure characteristics of general aircraft configurations. However, it was also felt that even wind tunnel testing techniques are not completely satisfactory.

This paper does a very good job of stressing the importance of remembering the various approximations and possible sources of error that are involved in designing practical airplane configurations in accordance with boom minimization concepts.

M-51
MEASURED AND CALCULATED SONIC BOOM SIGNATURES FROM SIX NONAXISYMMETRIC WIND-TUNNEL MODELS
H. L. Runyan, H. R. Henderson, O. A. Morris, and D. J. Maglieri
NASA SP-255, Third Conference on Sonic Boom Research, 1970, pp. 341-350

This paper presents the results of a wind tunnel experiment using six models conducted at $M = 2.7$ to study the growth of the pressure field as a function of distance from the model. The models consisted of two delta and four rectangular planforms including one model with side plates.

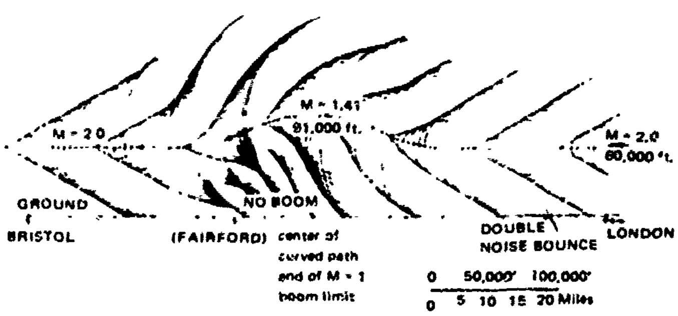
The results indicated a rapid transition from two-dimensional flow characteristics, known to exist near the model lower surfaces, to the three-dimensional characteristics measured in the tests. In general, good agreement was obtained between the measured and calculated pressure field using conventional techniques for three-dimensional flow analysis, especially at the larger distances. The exception was the model for which two-dimensional flow was forced to exist within the confines of side plates. For that model good agreement was obtained using two-dimensional flow theory, particularly at the smallest distance of about one body length. At the farthest measurements point, five body lengths, better agreement was obtained using three-dimensional flow theory. It is concluded that these results serve as a reminder that minimum sonic boom concepts based on two-dimensional reasoning can be very misleading and that the rapid development of three-dimensional flow is significant and must be taken into account.

The same conclusion was reached as the result of an earlier more limited investigation by Runyan and Henderson (see capsule summary M-35).

M-52
LOCAL AVOIDANCE OF SONIC BOOM FROM AN AIRCRAFT
W. F. Hilton
The Aeronautical Journal of the Royal Aeronautical Society, Vol. 75, March 1971, pp. 179-181

This paper discusses the use of curved flight paths in order to prevent the sonic boom of a supersonic aircraft from being heard in a chosen local region on the ground. The analysis is based upon the behavior of Mach waves, but it is expected that shock waves of finite amplitude will behave in a similar way.

The zone of zero boom dealt with here arises when the cusp resulting from an aircraft undergoing a pullup-pushover maneuver does not touch the ground. This concept is illustrated in the figure below, which was taken from this paper. The cusp below the aircraft track is quite well defined in several cases. During the pull-up the aircraft throws down a convex shock pattern, which reaches the ground. During the push-over, the downward shock is concave, reaches a focus, and travels upwards again. This gives the zone of "no boom." Below these cusps the circles do not intersect and no boom would be heard. This area is more than 10 miles long.



Avoidance of sonic boom by pull-up in vertical plane at M = 2

Assuming the aircraft climbs to a height h in a radius R at a Mach number M, an expression is derived relating the required accleration $f = M^2a^2/R$ to the Mach number and speed of sound:

$$(fh/a^2) = M(M-1)$$

This expression shows that if acceleration f is to be minimized, the lowest supersonic M at the highest possible altitude should be selected for the apogee of the maneuver.

As stated by the author, this paper is intended to start discussion rather than to present a finished case. A more thorough investigation would be required to determine if the concept discussed here is feasible.

Batdorf (see capsule summary M-59) did make a further analysis of the possibility of local sonic boom avoidance. He found that there is no region of "no boom" for the maneuver described by Hilton. The reader is referred to the above capsule summary for details.

M-53
SONIC BOOM MINIMIZATION INCLUDING BOTH FRONT AND REAR SHOCKS
A. R. George and R. Seebass
AIAA Journal, Vol. 9, No. 10, October 1971, pp. 2091-2093

The problem of aircraft shaping for minimum shock strengths taking account of midfield effects is treated in this paper. The analysis parallels that made by George in an earlier paper (see capsule summary M-41) except that both the front and rear shocks are treated in the present investigation, whereas only the front shock was treated in the earlier paper.

The results show that when both the front and rear shock are minimized the minimum values obtained are not as low as when only the front shock is minimized. However, these minimum values are still lower than the far-field lower bounds of Jones (see capsule summaries M-6 and M-16).

M-54
AIRPLANE CONFIGURATIONS FOR LOW SONIC BOOM
Antonio Ferri
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 255-275

This paper is exactly the same as the one summarized in capsule summary M-44. The reader is referred to that capsule summary for details of this work.

M-55
NON-ASYMPTOTIC EFFECTS IN THE APPROACH TO THE FAR-FIELD SONIC BOOM
LeRoy F. Henderson
Zeitschrift fur Angewandte Mathematik und Physik (ZAMP), Vol. 22, 1971, pp. 1103-1125

Whitham's non-asymptotic formula (see capsule summary G-3) for the bow shock overpressure of a body in supersonic flight is expanded in this paper in terms of a small parameter ϵ, which depends upon the F-function of the body. This expansion corresponds to small departures from an N-wave that result as one moves toward the body. The series is used to determine how changes in the equivalent body shape can modify the signature in the region of approach to the far-field.

Transformations which allow improved convergence of the series are discussed, and application is then made to some particular bodies. Three types of bodies were selected to illustrate the analysis: (a) cone-cylinder; (b) body with one or more vanishing derivatives; and (c) a body with a sine wave F-curve. The resulting expansion for each of these bodies is determined.

The reduction of sonic boom overpressure in the region of approach to far-field is then investigated. It is pointed out that body shape information can be used to reduce the boom at a given miss distance only when the N-wave has not yet formed. Thus the first step to reduce the boom is to ensure that $h<h_N$, where h is the altitude (or miss distance) of the body and h_N is the altitude (or miss distance) at which an N-wave is formed. It is shown that the N-wave miss distance can be increased merely by reducing $F_0 = F(\tau_0)$, where τ_0 is the value of τ which maximizes

$$\int_0^{\tau} F(\eta)d\eta.$$

This involves making the body smoother. A simple equation giving F_0 and F_0' for minimum boom is then derived.

The analysis then goes on to show how to reduce the boom by striking an optimum between two opposing effects. The first effect is most pronounced when the body has a well-developed shoulder and when the ground level miss distance is close to the N-wave formation miss distance, $h_g \to h_N$. For this case the action of the equation giving F_0 and F_0' for minimum boom is to move the centroid of the F-curve forward toward the apex of the body. This promotes a stronger shock in the near field, which is then decayed more rapidly in the far-field. The furthest development would be a pair of N-waves, in which the F-curve of the body would be a pair of delta functions at the front and rear. In physical terms, a strong shock is generated in the very near field by a blunt or nearly blunt body, and the shock is then almost immediately decayed by a closely spaced expansion fan.

The opposing effect is most pronounced when the body is smoother, and when the ground level is in the near field, $h_g<<h_N$. In this case the action of the equation giving F_0 and F_0' for minimum boom is to move the centroid of the F-curve backwards toward τ_0. The idea is to keep the shock as weak as possible in the near-field so that it will still be weak at $h = h_g$. This is accomplished by giving the body a shape which spreads out the compression waves and bunches up the expansion waves. The furthest development would again be a pair of delta functions but arranged differently. It is shown that the initial wave can be thought of as being the opposite of an N-wave. Hence the limiting condition is somewhat loosely called a reversed N-wave.

The effect of spreading of the characteristics is shown to give only a small reduction of the boom overpressure, and several numerical examples are then given of the procedure.

This paper is an extension of an earlier paper by Moore and Henderson (see capsule summary M-33). The derivations are carried out in more depth here and more cases are treated.

George (see capsule summary M-41) also considered how to modify the signature in the mid-field by manipulating the F-curve. He begins with some results obtained by Jones (see capsule summaries M-6 and M-16), who showed how the lower bound on the sonic boom could be obtained by reducing the F-curve to a pair of delta functions. George considered a redistribution of the positive part of the F-curve which retained the forward delta function but with a reduced area underneath it.

He was able to get a good reduction in the boom overpressure in the mid-field. In effect he worked backwards from the far-field to the mid-field by means of this redistribution.

M-56
LOWER BOUNDS FOR THE PRESSURE JUMPS OF THE SHOCK WAVES OF A SUPERSONIC TRANSPORT OF GIVEN LENGTH
L. B. Jones
Aeronautical Quarterly, Vol. 23, February 1972, pp. 62-76

In this paper the lower bounds for the pressure jumps across shock waves propagating through a homogeneous atmosphere are determined by considering both the bow and rear shock waves simultaneously. It is assumed that all the shocks have coalesced into bow or rear shocks, but not that the shocks are at such a great distance (asymptotic) that they have the same strength.

First, expressions are obtained for the pressure jumps across both the bow and rear shock waves in terms of the Whitham F-function in the range $o \leq x \leq 1$, that is, over the length of the supersonic transport. These expressions are necessary since the area/lift distribution and hence the resulting F-function can only be varied over this length. Having obtained these expressions an approximation to the pressure jump across the rear shock is developed, which is such that for positive values of the F-function the condition for minimum values for the pressure jump across the rear shock for a given constraint is the same as that for the asymptotic case treated previously by Jones (see capsule summary M-16). Using this approximation the form of the F-function which gives the lower bound value for the higher of the pressure jump across both the bow and rear shock waves is determined.

Using the above results, a family of shapes for the F-function is taken, and within this family the lower bound value for the higher of the pressure jumps across the bow and rear shock waves is evaluated without any approximation. The pressure jumps across the shock waves of other configurations are then evaluated to compare with the lower bound values obtained.

Off-design values for the pressure jumps across the shock waves are also evaluated and it is shown that not only can low values for the pressure jump be obtained at design conditions, but that, if care is taken in choosing the design condition, low values for the pressure jump across both the bow and rear shock waves can be obtained over the whole flight path of the supersonic transport.

This paper extends the theory developed by Jones in a previous paper (see capsule summary M-42), which treated only the bow shock.

George and Seebass (see capsule summary M-26) made a similar analysis of sonic boom minimization including both front and rear shocks.

M-57
SUPERSONIC TURNS WITHOUT SUPERBOOMS
H. S. Ribner
University of Toronto, Institute for Aerospace Studies, UTIAS Technical Note No. 174, February 1972

This paper presents an investigation into flight procedures which would enable supersonic turns to be made without the production of superbooms, or regions of focus, on the ground. Superbooms normally occur on the inside of a turn due to the focussing of the rays in that region.

It is shown that ray focussing will not occur if the aircraft is slowed down as it makes the turn. The correct deceleration will eliminate the local curvature of the wave front responsible for focussing. The curvature (concave outward) is proportional to the component of resultant acceleration resolved along the normal to the wave front. The correct deceleration is shown to be such that the tangential deceleration resolved along the normal to the wave front is of the right magnitude to cancel out the centripetal acceleration similarly resolved.

Rao's theory (see capsule summary P-12) is used to derive the relation between turning angle and Mach number such that no focussing occurs. This relation is:

$$\frac{d\mu}{dt} = \frac{d\phi}{dt}$$

where μ = Mach angle

and $d\phi/dt$ = rate of turning of aircraft path.

Thus the initial and final Mach angles are related to the total turning angle by

$$\mu_2 - \mu_1 = \phi$$

Hence the slowing down required by the no-focus condition increases the Mach angle μ by precisely the angle of turn ϕ. This dictates an upper limit to ϕ for a given initial Mach number such that the final Mach number will not be subsonic.

The locus of focussed booms in three-dimensions is shown to be a cylinder. Equations are then derived which give the minimum radius of curvature of the flight path, the maximum centripetal acceleration, and the corresponding maximum permissible airplane bank angle ϕ for which focussed booms will not reach the ground due to the effects of atmospheric refraction. The minimum turn radius (- maximum acceleration) for focus cutoff is shown to be related to the tabulated width of the sonic boom carpet for rectilinear flight by the following simple equation:

$$R\cos^2\mu_g = B$$

where R = minimum turn radius
μ_g = Mach angle at ground level
and B = boom carpet half-width

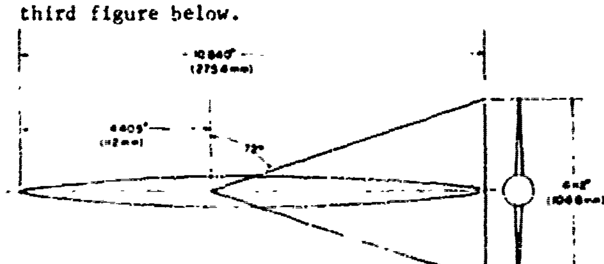
Hilton (see capsule summary M-52) presented a method for preventing the sonic boom from reaching a chosen local region on the ground. The method was based upon the execution of a pushover maneuver at the appropriate time. That study was complementary to the present one in that it dealt with straight flight paths, while the present one deals with superboom avoidance for curved flight paths.

M-58
EXPERIMENTAL VERIFICATION OF LOW SONIC BOOM CONFIGURATION
Antonio Ferri, Huai-Chu Wang, and Hans Sorensen
NASA CR-2070, June 1972

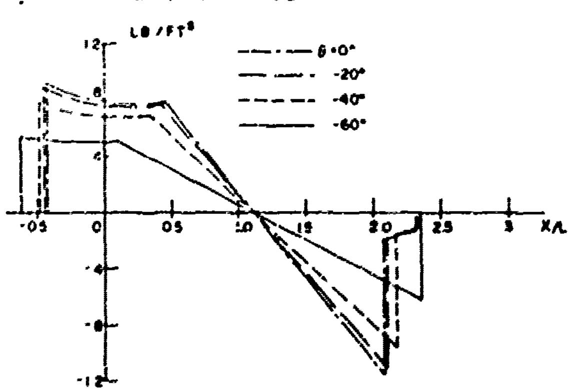
This report presents the results of an analytical and experimental investigation into the reduction of sonic boom overpressures through airplane configuration design. The experiments were performed at the Aeronautical Research Institute of Sweden by the research group headed by Professor M. Landahl and Dr. G. Drougge. The experimental technique developed by the group (see capsule summary G-62) based on the higher order analysis developed by M. Landahl, I. L. Ryhming, and others (see capsule summary G-41) was used.

The model was designed by a research group at the Aerospace Laboratory of New York University as part of an investigation of low boom configurations (see capsule summaries M-24 and M-44). The model was designed to produce an overpressure of the order of 1 psf.

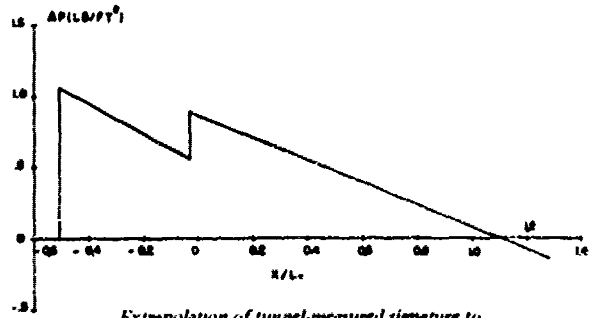
The experimental technique, method of data analysis, and configuration characteristics are discussed in some depth. The figure below, which was taken from this paper, shows the overall design of the model tested. The analysis of the sonic boom was performed for the conditions corresponding to cruise at 60,000 feet, M = 2.70, and total weight equal to 460,000 pounds. The theoretical analysis followed the method outlined by Carlson (see capsule summary G-23), which transforms the lift into an equivalent area. The lift was determined by means of a second order theory with some approximate second order corrections. The extrapolation of the signature to ground level was performed by use of the Hayes' program (see capsule summary P-98). The sonic boom signatures obtained from this theoretical analysis are shown in the second figure below for four different meridian planes. The experimentally determined signature is shown in the third figure below.



Design of airplane configuration



Theoretical pressure signatures, L = 300 ft, h = 60,000 ft, W = 460,000 lb, M = 2.7



Extrapolation of tunnel-measured signature to $r/L_0 = 200$, for $L_0 = 300$ ft

The following conclusions were reached as a result of this investigation.

1. Sonic booms having peak values of the order of 1 psf were measured, as predicted analytically. The sonic booms obtained had near-field signatures. The distribution of equivalent cross-sectional area tested corresponds to an airplane shape that has the volume, length, and lift requirements of a practical airplane configuration; however, substantial additional work is required to investigate if all other aerodynamic requirements related to a practical configuration can be met.

2. The nonlinear and three-dimensional effects are of primary importance for the determination of the correct values of the sonic boom from measurements at small distances from the model. More complex experimental techniques where such effects are determined are required when near-field measurements are made.

3. The experimental method proposed by Landahl, et al (see capsule summary G-62) gives satisfactory results.

4. Improvements are still required in the experimental techniques and in the analysis in order to measure and determine with better accuracy all of the required quantities.

This experiment did demonstrate that an aerodynamic configuration designed to take advantage of near-field effects can generate maximum overpressures on the order of 1 psf.

M-59
ON SONIC BOOM AVOIDANCE
Dr. S. B. Batdorf
Aeronautical Journal, September 1972, pp. 541-544

This paper looks further into the suggestion by Hilton (see capsule summary M-52) that local sonic boom avoidance can be obtained for a chosen region on the ground by executing the proper pullup-pushover maneuver. In the present study, as in Hilton's, pressure disturbances are assumed small so that they move at sonic speed.

It is shown that there is no region of "no boom" for the maneuver described by Hilton. Regions of single, double, and triple shocks were found, but no shockless region. The author concludes that Hilton arrived at an incorrect conclusion simply because he did not carry the construction far enough.

The author then goes on to show that no maneuvers in the vertical plane will result in boom avoidance. However, when the altitude is high and the change of direction during the maneuver is large, the corresponding shocks may be quite weak.

Immediately following the above discussion is a comment by Hilton in which he states that he was aware that the "boomless" region below the concave flight path would be invaded by a shocklet from the preliminary convex part of the flight path, but not of the triple boom. He then goes on to show that the "shocklet" will be of a reduced strength, probably sufficient to make the sonic boom acceptable.

Immediately following the above comment is a comment by Batdorf in which he discusses the effects of defocussing on shock intensity.

M-60

OPTIMUM CONFIGURATIONS FOR BANGLESS SONIC BOOMS
Wallace D. Hayes and Francis B. Weiskopf, Jr.
Quarterly of Applied Mathematics, October 1972, pp. 311-328

This paper presents derivations of optimum configurations for a supersonic aircraft subject to the condition of a bangless sonic boom. A bangless sonic boom is defined here as one having no shock waves in the signature at the ground. The aircraft is represented by a fore-and-aft line distribution of either lift or volume elements. The case considered is that of the sonic boom from an aircraft in uniform level flight in a stratified atmosphere. The approach used is that of Hayes, Haefeli, and Kulsrud (see capsule summary P-98) in which a suitable phase variable and invariant signal strength variable are identified, and signal distortion is calculated using an appropriate age variable.

Several optimization problems are posed, subject to the condition that a shock wave appears only incipiently in the pressure signature at a given point. These problems are solved using the calculus of variations with inequality constraints, together with a nonlocal isoperimetric relation and only an upper bound on the control variable, F'(x). Here F(x) is the Whitham F-function. By placing an upper limit on F'(x), the F(x) curve does not become multivalued after being "tilted" by the use of the age variable.

An equation giving the maximum effective gross weight of an aircraft (defined to be the actual weight plus $\rho_a U^2$,$^{-1}$ times the increase in exit area over capture area for the aircraft engines, where U is the aircraft speed) of given length under given flight conditions is the principal result. This equation is:

$$W = \frac{128\gamma^{1/2}\beta^{1/2}g^{1/2}\rho_a a_a L^{5/2}(\cos\phi)^{1/2}}{135(\gamma+1)\pi^{1/2}M^2\,\mathrm{erf}(\zeta)}$$

where γ = ratio of specific heats

$\beta = \sqrt{M^2 - 1}$

M = Mach number

g = gravitational acceleration

ρ_a = density at aircraft altitude

a_a = sound speed at aircraft altitude

L = effective aircraft length = distance over which distribution of lift on volume elements can be non-zero

ϕ = angle variable in a cylindrical coordinate system aligned with the aircraft axis

$\zeta = (1/2\alpha r)^{1/2}$

r = radial cylindrical coordinate = distance from aircraft flight axis

and $\alpha = \gamma g \cos\phi / a_a^2$.

From this formula it can be seen that the allowable gross weight is greatest at a low supersonic Mach number, and it is very sensitive to length (proportional to $L^{5/2}$). Due to the dependence of W upon ρ_a, the allowable gross weight decreases with increasing altitude. In comparison, the formula derived by Jones (see capsule summary M-6) for the maximum gross weight attainable with a given shock strength ΔP on the ground, assuming an asymptotic N-wave shows the allowable gross weight to be relatively insensitive to Mach number, only weakly dependent upon effective length and proportional to the flight altitude.

Previous sonic boom optimization studies (see capsule summaries M-16, M-37, M-42, M-53, M-56, M-61, M-43) were based upon a signal which was not an N-wave, but the presence of a shock wave was accepted. These studies concentrated either on minimizing the strength of the bow shock or on minimizing the strengths of both the bow shocks and tail shocks. The present study was the first to treat the bangless boom optimization problem.

In an earlier paper (see capsule summary M-49) Hayes, et al presented a similar, but less extensive analysis of bangless boom optimums.

M-61

SONIC BOOM MINIMIZATION
R. Seebass and A. R. George
J. Acoust. Soc. America, Vol. 51, No. 2 (Part 3), 1972, pp. 686-694

This paper gives general rules for determining the minima for given signature parameters, such as overpressure and shock pressure rise, for the full signature (including both front and rear shocks). Also, a figure of merit is introduced which makes it possible to judge the effectiveness of exotic boom minimization schemes.

The general rules for determining minima for given signature parameters are derived starting from the expression

$$F(y) = \begin{cases} A\,\delta(y) + By + C, & 0 \le y \le \lambda \\ By - D, & \lambda \le y \le \ell \end{cases}$$

Here A, B, C, and D are constants which are determined by the specified characteristics of the shock wave such as rise time, ratio of the front and rear shock strengths, etc. and by constraints on the F-function itself. Expressions are derived which allow the following to be calculated: (1) minimum value of the shock pressure rise; (2) minimum overpressure; (3) overpressure for minimum impulse; and (4) the maximum pressure in the signature when the shock pressure rise is minimized.

Numerical examples for a specific airplane configuration are then given. These examples show that improvements in shock pressure rise and overpressure accrue at the expense of increased impulse.

Finally, the following figure of merit is proposed for evaluating exotic sonic boom minimization schemes.

$$(P_g \ell_{eff}^2/W)(h/\ell_{eff})^{1/2} e^{-h/2H}$$

where P_g = ambient pressure at ground level

ℓ_{eff} = effective aircraft length

W = aircraft weight

h = aircraft altitude

and H = atmospheric scale height.

It is stated that for typical SST aircraft this quantity is about 10^3, and significant improvements in sonic boom characteristics can be anticipated for aircraft that achieve values greater than $5 \cdot 10^3$.

The topic of sonic boom minimization including both front and rear shocks was also treated in another paper by George and Seebass (see capsule summary M-53). However, the present paper treats the subject in greater depth.

A later paper by Seebass and George (see capsule summary M-62) draws heavily upon the information presented in the present paper.

M-62
SONIC BOOM REDUCTION THROUGH AIRCRAFT DESIGN AND OPERATION
A. R. Seebass and A. R. George
AIAA Paper No. 73-241, Presented at AIAA 11th Aerospace Sciences Meeting, Washington, D.C., January 10-12, 1973

This paper discusses means of reducing or eliminating the sonic boom through aerodynamic design or aircraft operation. These include designing aircraft to minimize or eliminate certain features of the pressure signature, operating aircraft at slightly supersonic speeds so that the sonic boom does not reach the ground, and seeking reductions through the high altitude-high speed flight conditions of hypersonic transports.

The general rules derived in an earlier paper by Seebass and George (see capsule summary M-61) for determining the minimum impulse, minimum overpressure, and minimum shock pressure rise are reviewed and examples showing the effect of varying aircraft weight, length, altitude and Mach number are given. These examples showed the following:

1. The overpressure is insensitive to Mach number, and the impulses decrease slightly with increasing Mach number.
2. There is a weight below which, for the prescribed conditions of h = 60,000 feet, L = 300 feet, and M = 2.7, there need be no shock. Also, the impulse is essentially proportional to aircraft weight.
3. It is always beneficial to increase the aircraft's length and stretch out the pressure signal.
4. The minimum overpressure is insensitive to altitude and the impulse grows exponentially with increasing altitude.

From these results it is concluded that if both the overpressure and impulse are important, supersonic aircraft may have to be designed to fly at altitudes comparable to those of present subsonic jets.

Methods of reducing sonic boom through aircraft operation are then discussed. In connection with the operation of aircraft at supersonic speeds below the threshold Mach number an equation is given which describes the sound field below the caustic. It is stated that this equation was derived from an asymptotic expansion of the results of a linear theory. The equation is as follows:

$$\Delta P = \Delta P_N (y_N/y)^{1/4} \varepsilon^2 \, S(T,\varepsilon) \text{ with}$$

$$\varepsilon = 3\lambda/4(\alpha y^3)^{1/2}$$

where ΔP = overpressure

ΔP_N = overpressure of an incident N-wave of length λ at a distance y_N above the caustic surface

y = distance below caustic

α = gradient of the square of the aircraft Mach number based upon its speed U and the ambient sound speed

$S(T,\varepsilon)$ is defined by curves given in the paper.

$T = 2Ut/\lambda$

U = aircraft speed

and t = time

The results of this equation are summarized as follows: The distance below the caustic at which the maximum pressure is comparable to the overpressure of the incident signal, at that same distance above the caustic, is approximately $k\lambda^{2/3}$, where k is approximately $22(ft)^{1/3}$ for the standard atmosphere. For λ = 300 ft the maximum over-

pressure 1,000 feet below the caustic has the same magnitude as the overpressure of the incident N-wave 1,000 feet above the caustic. In an additional 1,000 feet the maximum pressure will decrease by a factor of 10. Far below the caustic surface the pressure decays rapidly (as the 13/4 power of the distance from the caustic) and soon the signal contains only subaudible frequencies. The details of the pressure field where the shock terminates cannot be determined using this equation.

In connection with hypersonic transports, a theory developed earlier by Seebass (see capsule summary C-47) for determining the sonic boom of a hypersonic vehicle is reviewed. The results of numerical examples indicate that the overpressures and impulses obtained at realisti flight altitudes may be less than those achieved by the minimum overpressure designs for supersonic aircraft. However, as in the case of the supersonic transport, the impulse of the hypersonic transport increase exponentially with altitude. It is therefore concluded that there does not seem to be much refuge in high altitude hypersonic flight.

This is an excellent discussion of sonic boom minimization concepts, as was the similar earlier paper by Seebass and George (see capsule summary M-61). The expression given for the sound field below a caustic could prove to be a significant contribution to sonic boom theory if its validity can be experimentally demonstrated.

M-63
SOME EFFECTS OF WING PLANFORM ON SONIC BOOM
Lynn W. Hunton, Raymond M. Hicks, and Joel P. Mendoza
NASA TND-7160, January 1973

The results of a wind tunnel investigation into the effects of wing planform on sonic boom are presented in this paper. Twelve different wings having a constant wetted area and volume in combination with a fixed body were tested in the Ames 9- by 7-foot and 8- by 7-foot supersonic wind tunnels at Mach numbers of 1.68, 2.0, and 2.7. These models and some of the results of these tests are shown in capsule summary M-31.

The following conclusions were reached as a result of these tests:

1. Agreement of sonic boom theory with experiment was found to depend generally on configuration slenderness, the type of signature, and the distance ratio.

2. The degree of complexity of wing planform shape appears to have little bearing on the accuracy with which signature characteristics were predicted for either the very near-field or mid-field distance ratios.

3. Because of the nonlinear distortions that occur in the propagation of a waveform in the atmosphere, direct comparisons of very near-field signatures are not a valid guide to the relative level of overpressure performance for a given configuration at mid-field distances.

4. Wing planform can significantly reduce the magnitude of shock overpressures at mid-field distances by about 20 to 40 percent in comparison with the overpressures for conventional wing planforms.

5. Local changes in wing leading-edge shape obtained with strakes, cranks, or curvature were relatively ineffective in altering the overpressure characteristics of the basic planform.

6. Supersonic aircraft designed for low sonic boom at a specific Mach number will not have broad application over the full supersonic Mach number range nor will such designs be in consonance with design features that produce maximum aerodynamic efficiency and performance.

M-64
SONIC BOOM
Wallace D. Hayes
In Annual Review of Fluid Mechanics, Vol. 3, M. Van Dyke, et al, eds., 1971, pp. 269-290

This paper presents a summary of the state of the art of sonic boom theory as of 1971. Included in the discussion is a description of a transition maneuver for avoiding the superboom produced by an aircraft as it accelerates to supersonic speeds. The reader is referred to capsule summary S-42 for a description of this maneuver.

M-65
APPLICATION OF SONIC-BOOM MINIMIZATION CONCEPTS IN SUPERSONIC TRANSPORT DESIGN
Harry W. Carlson, Raymond L. Barger, and Robert J. Mack
NASA TN D-7218, June 1973

The study described in this paper uses near-field sonic boom minimization concepts to investigate the design of a large (234 passenger) low-boom supersonic transport. Four SST design concepts are studied, two of which are considered to be conventional approaches with only modest modifications for sonic boom benefits and two others which depart from conventional practices in accordance with the dictates of sonic boom minimization concepts. In order to provide a realistic first estimate of the applicability of these concepts, the analysis accounts for the influence of airplane configuration on aerodynamics, weight and balance, and performance.

The results of the investigation show that shock strengths of somewhat less than 1 psf for a design range of 2500 nautical miles and a cruise Mach number of 2.7 are within the realm of possibility. It was found that an important design feature of such an airplane is a wing of large area and long root chord located well aft with respect to the fuselage. The wing would incorporate twist and camber designed to meet sonic-boom shaping, as well as drag minimization requirements, and would employ positive dihedral. It was also found that a canard surface may be utilized in optimization of the lift distribution for sonic boom benefits.

It is concluded that, because many of the design features are in direct contradiction to presently accepted design practices, further study by qualified airplane design teams is required to ascertain sonic boom shock strength levels actually attainable for practical supersonic transports. (The results of a preliminary design study of this nature, conducted by The Boeing Co., are summarized in capsule summary M-66.)

This is an excellent paper. It presents a good summary of the present state of the art of sonic boom minimization theory and the manner in which this theory is applied to airplane design.

M-66
A STUDY TO DETERMINE THE FEASIBILITY OF A LOW SONIC BOOM SUPERSONIC TRANSPORT
Edward J. Kane
NASA CR 2332, September 1973

The objective of this study was to determine if a supersonic transport concept that was designed to produce a sonic boom signature with low overpressure represented a feasible configuration. The design goal was to achieve values of overpressure and impulse during cruise which were significantly below those produced by current SST designs. Specifically, the following two goals were chosen: An overpressure of 1.0 psf or less for a cruise Mach number of 2.7 and an altitude of 55,000 ft; and an overpressure of 0.5 psf for a cruise Mach number of 1.5 and an altitude of 45,000 ft. Technology projected for the 1985 time period was assumed for purposes of the analysis. The principal effort was to develop a cruise configuration capable of meeting the sonic boom goal while accepting some compromises elsewhere in the flight profile. The Mach 2.7 goal was achieved with a blended arrow wing configuration. For cruise at the design altitude this airplane has the potential of carrying 183 passengers a distance of 3780 n.mi. The Mach 1.5 design was a low arrow wing configuration with a horizontal tail. This airplane did not quite achieve the design goal because the tail shock during cruise was about 0.7 psf. For cruise at the design altitude this airplane has the potential of carrying 180 passengers a distance of 3220 n.mi. Both airplanes exhibited some rather serious difficulties in terms of complying with normal design constraints. Even though the scope of this study was limited the results indicate that an advanced technology SST with a low sonic boom level appears to be a feasible concept.

The study described here is of the type recommended by Carlson in the paper summarized in capsule summary M-65. This was the first attempt made by a qualified airplane design team to design a supersonic transport with sonic boom constraints as the prime consideration.

5.0 HUMAN RESPONSE AND SOCIAL CRITERIA

HRSC-1

GROUND MEASUREMENTS OF THE SHOCK-WAVE NOISE FROM AIRPLANES IN LEVEL FLIGHT AT MACH NUMBERS TO 1.4 AND AT ALTITUDES TO 45,000 FEET

Domenic J. Maglieri, Harvey H. Hubbard, and Donald L. Lansing

NASA TN D-48, September 1959

In this experiment ground pressure measurements were made of the sonic boom resulting from six flights of an F-101 fighter at Mach numbers from 1.15 to 1.40 and altitudes from 25,000 to 45,000 feet and one flight of an F-100 fighter at a Mach number of 1.13 and an altitude of 35,000 feet. Most of the results deal with sonic boom propagation and for a summary of these the reader is referred to capsule summary P-20. Only the brief portion of the paper dealing with human response will be summarized here.

Two main conclusions concerning human response were reached as a result of comments made by observers of these flights:

1. In cases where measured ground pressures exceeded values of about 1 psf for a steeply rising wave shape, most observers considered the noise objectionable and likened it to close-by thunder.

2. There was an indication that the wave shape might be as important as the pressure magnitude with regard to observer reaction.

This was one of the first controlled flight experiments in which an attempt was made to relate the reactions of observers to measured sonic boom overpressures.

HRSC-2

SOME SPECIAL PROBLEMS CONNECTED WITH SUPERSONIC TRANSPORTS

Bo Lundberg

Symposium on Supersonic Transport, Vol. 2, Working Papers, IATA 14th Technical Conference, Montreal, April 17-21, 1961

This paper deals with sonic booms and cosmic radiation as related to commercial supersonic aviation. Only the discussion dealing with sonic booms will be summarized here.

The discussion concerning sonic booms is very general and deals mainly with their effect on people. The basic conclusions reached are the following:

1. Pressure rises at ground level caused by a supersonic airliner would be unacceptable for operation over both densely and sparsely populated land areas, because of disturbance to people and risk of damage to property and harm to animals.

2. Ships and their passengers and crews would be similarly affected by over-water operations; it therefore seems probable that supersonic flights between the continents would also encounter heavy opposition.

3. A study of possible scheduling for North Atlantic flights showed that for this scheduling to be convenient and allowing reasonable turn-around times, it will hardly be possible to utilize a supersonic airliner for more than one return flight per 24-hour day.

This is a very general discussion which was made at a time when very little was definitely known concerning the effects of sonic booms on people and structures. Many of the above conclusions are based on personal conjecture by the author, especially those concerning danger to animals and operation over water and sparsely populated areas.

HRSC-3

SOME SPECIAL PROBLEMS CONNECTED WITH SUPERSONIC TRANSPORT

Bo Lundberg

The Aeronautical Research Institute of Sweden, FFA Memo PE-11, 1961

This paper is the same as the one discussed in capsule summary HRSC-2. The reader is referred to that capsule summary.

HRSC-4

SUBJECTIVE RESPONSE TO SONIC BANGS

M. J. Clarke and J. F. Wilby

C. P. No. 588, British A.R.C., 1962

In this report the response of the ear to short duration bursts of noise is discussed. The information is used in an attempt to predict human reaction to sonic booms heard inside and outside a building.

The pressure waveform heard by an observer on the ground is assumed to be in the form of a simple N-wave. The time interval between front and rear shocks is estimated to be 0.20 - 0.25 seconds for a slender delta airliner flying at $M = 1.8$ at 60,000 feet.

For a range of values of boom duration, the transmission loss based on peak levels is estimated for typical window pane sizes and thicknesses and is found to vary between 12 and 40 dB, the higher values being for smaller, thicker panes. Sound levels inside a building, neglecting reverberation effects, are estimated, assuming a peak pressure level for the shock wave of 1 psf, to be between 60 and 110 dB.

For a large room it is estimated that the reverberant effect increases the apparent loudness inside by about 5 dB which with a transmission loss for that particular case of about 15 dB, results in an apparent decrease in loudness inside the room, relative to the outside, of about 10 dB. This means that, neglecting the effect of surprise, a sonic boom in this case will be less frightening when heard inside than when heard outside. A similar conclusion is reached when considering smaller rooms equivalent in size to living rooms in a house.

The conclusion reached in this paper that a sonic boom will be less frightening when heard inside than when heard outside does not agree with the later experimental findings of Broadbent and Robinson (see capsule summary HRSC-8). They found that the upper limit of acceptable boom overpressure, as measured outdoors, was 2.3 psf when heard outdoors and 1.9 psf when heard indoors. The disparity between those results and the results of the present paper may be due to the neglect in the present paper of the effect of startle and a correct accounting of the effect room vibration.

HRSC-5

GAINING PUBLIC ACCEPTANCE OF SONIC BOOM PHENOMENON THROUGH PUBLIC RELATIONS

William H. Martin

M. S. Thesis, Boston School of Public Relations and Communications, AD 404458, 1963

This study attempts to show how the United States Air Force has applied an intense program of public relations toward gaining public tolerance of sonic booms. The Air Force campaign of briefings, publicity, and handling of citizens' complaints was investigated through inspection of Air Force official records and joint Air Force-commercial campaign materials.

As a result of the study of the technique used by the Air Force, the following conclusions were reached concerning a public relations program aimed at gaining public acceptance of sonic booms generated by commercial supersonic transports:

1. Any program of public relations, to be successful, would require the fulfillment of a social responsibility that made every consideration for the public's peace of mind in planning the flights.

2. A public philosophy would be needed which kept a constant finger on the pulse of public opinion, and reacted with prompt measures to counteract any unfavorable trends in public opinion. This would require a staff of public relations experts who would personally investigate any claims of damage done by commercially-caused booms, and the exercise of a sincere concern for the rights of the individual. In cases wherein responsibility for damage can be shown to rest on the commercial firms, payment must be prompt and complete.

3. The "control of truth" must be handled in such a way that individuals likely to hear booms from commercial planes will know what to expect and know that the airlines have planned their flights so that the minimum disturbance would be caused on the ground in the path of flight.

4. A preliminary program of promotion of supersonic aircraft would likely be necessary to prepare the public for the noises of the expected flights.

5. The linking of supersonic commercial flights with some generally-accepted theme would be highly desirable in order to form in the minds of the general public a "good image." This association would in all likelihood be necessary to persuade the majority of Americans who do not fly on commercial aircraft to tolerate commercial booms.

This is one of the few studies done concerning public relations and the sonic boom. Many of the above conclusions were reinforced by the Oklahoma City sonic boom program (see capsule summaries HRSC-11 and HRSC-14).

HRSC-6

ON THE SUBJECTIVE ASSESSMENT OF SONIC BOOMS

E. J. Richards

Aeronautical Research Council Report No. A.R.C. 25899, N. 291, May 11, 1964

The object of this paper is to point out some of the parameters that affect subjective response to sonic booms. Some of these parameters are: (a) degree of minority opinion constituting a nuisance, (b) frequency of occurrence, (c) time of day or night, (d) nature of the N-wave from aircraft at various heights and speeds, (e) indoors or outdoors, (f) ground floor or upstairs, (g) types of windows and room reverberation, and (h) reflections and focussing.

Based upon the tentative examination of each of these parameters the following conclusions were reached:

1. The establishment of the overpressure amplitude in ideal conditions is only a starting point for the establishment of a critical (acceptable) level. There are many other parameters that are equally if not more important. These variables may possibly all, in seriously adverse conditions, modify the acceptability by a factor, equivalent to a reduction of the sonic boom amplitude to a quarter of its original strength.
2. The factors involved are, in practice, all hopelessly inter-related. A final acceptability judgment will probably be possible only after extensive controlled supersonic flights over populated areas are made.

Most of the early parametric studies involving the effect of sonic boom constraints on airplane design and performance dealt only with the sonic boom overpressure (see capsule summaries OAP-2, OAP-4, OAP-5, OAP-6, OAP-7 and OAP-8). This paper was one of the earliest to point out that there are other characteristics of the sonic boom pressure signature that are just as important as overpressure, and minimizing overpressure will not necessarily minimize public annoyance.

HRSC-7

ANALYSIS OF POPULATION SIZE IN THE SONIC EFFECTS ZONE ALONG LIKELY SST ROUTES

G. Baughman, A. Whiting, D. Finley, J. Andrews, O. Goehring, R. Ferris, and G. Sexton

Federal Aviation Agency, SST Memorandum No. 507, October 1964

This is a report on a preliminary study to determine the effects on population resulting from supersonic transport operation. For the purposes of this study the SST flights are considered to be from 1200 to 3470 n. miles in length, and the sonic boom effects zone is defined as a strip 50 n. miles wide extending along the routes except for 100 n. mile segments at origin and destination which are used for subsonic climb-out and descent.

Estimates of the number of inhabitants exposed to sonic booms along nineteen selected domestic and

ten selected international great circle routes are determined on the basis of the 1960 census and a population forecast for 1975. Route populations are also obtained for modified domestic and international routes configured to avoid high population density areas and for domestic routes running parallel to the great circle routes. A further analysis was made to estimate the number of sonic booms expected to affect various portions of the United States population during a given twenty-four hour period.

The following conclusions were reached as a result of this analysis:

1. The medium range route from New York to Denver was found to be the domestic route affecting the largest population. The longer route from Los Angeles to Boston involved the second largest number of inhabitants.

2. A comparison made of the number of inhabitants affected by overflight along five great circle routes and modified routes indicated that a reduction of route population by a factor of ten may occur when the slightly longer routes between these points are used. The great circle route between New York and Houston, however, was found to include a smaller number of inhabitants than either of the two modified routes selected to avoid high population centers.

3. For the route structure investigated (see table below, which was taken from the paper), it was found that over 80% of the land area and slightly over 60% of the population would be subjected to sonic booms. About 23% of the total area and 24% of the population would be subjected to an average daily rate of 10 or more booms. Four percent of the land area and slightly over 1% of the population would fall within the 35-51 boom category.

Western City	Eastern City	No. of Daily Round Trips
[illegible]	New York	2
[illegible]	[illegible]	
[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]
[illegible]	Washington	[illegible]
[illegible] Angeles	[illegible]	[illegible]
Los Angeles	New York	[illegible]
[illegible]	Washington	[illegible]
[illegible]	Miami	
Los Angeles	Miami	
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	
[illegible]	[illegible]	2
Minneapolis-St Paul	[illegible]	[illegible]
Los Angeles	Chicago	[illegible]
Houston	New York	
Los Angeles	Cleveland	[illegible]
Los Angeles	[illegible]	
[illegible]	New York	[illegible]
San Francisco	Chicago	[illegible]
Seattle	Chicago	[illegible]
[illegible]	Chicago	
[illegible]	[illegible]	[illegible]

Number of Flights Connecting City Pairs

4. It may be possible to reduce the size of the 35-51 zone, but to eliminate the highest region entirely seemed difficult since some of it was caused by the inevitable coalescing of routes coming into Los Angeles.

5. There are certain factors which will greatly limit the extent to which high boom areas and the number of people affected can be reduced. These are: (a) There is already a high concentration of people in the zone receiving no booms; it is doubtful that flights could be shifted in such a manner as to increase greatly the number of people in this region, (b) The amount of area covered by individual flights is minimal when the routes are direct. Dog-leg routes increase the area affected; (c) Rerouting flights to go over the Gulf of Mexico would be of small benefit since the area near the Gulf is already in a low boom range; (d) Rerouting flights in the high-frequency zones to areas that are not boomed would offer no improvement because most of the boom-free area is near the coast; flying along the coast would boom new areas and would not lessen the number of booms received in the central regions.

6. On the basis of the 1960 population census, flights from New York to Tel-Aviv and Paris to Cape Town affect 26.5 and 27.5 million persons--the largest numbers for the international routes selected.

7. By following modified "population-avoidance" routes, the populations affected along the New York to Tel-Aviv and Paris to Cape Town routes were reduced in number from 26.5 to 9.7 million and 27.7 to 6.8 million.

This is a very significant report in that this is the most extensive investigation conducted concerning the number of people that would be exposed to sonic booms if overland commercial supersonic flight ever became a reality.

HRSC-8
SUBJECTIVE MEASUREMENTS OF THE RELATIVE ANNOYANCE OF SIMULATED SONIC BANGS AND AIRCRAFT NOISE
D. F. Broadbent and D. W. Robinson
Journal of Sound and Vibration, Vol. 1, No. 2, 1964, pp. 162-174

The purpose of the experiments reported in this paper was to provide some rough estimate of the level at which sonic booms might become more annoying than ordinary aircraft noises. A secondary purpose of the experiment was to study the way in which reported annoyance increased as the sound pressure level increased.

Experiments were conducted on a total of seventy-nine subjects. In these experiments they were asked to estimate the relative annoyance of the sound of a jet aircraft, a piston-engined aircraft, and sonic booms, each of which was reproduced electronically at various levels. For the sonic booms, a sound typical of that heard inside a building was chosen. There were shortcomings in the reproduction of all three types of aircraft sounds. The jet aircraft and piston-engined aircraft noise reproductions both contained too much energy at high frequencies. The reproduced sonic boom was considerably degraded compared with the original due to frequency response limitations of the tape recorder available at the time and of the loudspeaker equipment, as well as the room acoustics. The principal deficiency in the reproduced sonic boom was lack of bass response, appreciable at 50 cycles/sec and almost total below

10 cycles/sec, although the original boom contained most of its energy at still lower frequencies.

The experimental procedure was as follows: Each of the subjects was asked to listen to the sound of the jet aircraft (at a prescribed level) and to regard that sound as representing 10 units of annoyance. Another sound was presented immediately after the presentation of this standard sound. This might be the jet noise again, the piston driven aircraft, or a sonic boom. The level could take any one of five values. Regardless of the nature of the second sound, the listener was to indicate the number of units of annoyance which he would think appropriate to it, as compared to the standard sound of 10 units.

The results showed that the increment necessary to double annoyance in the case of the jet and piston aircraft sound was about 13 PNdB. The rate of increase of annoyance with level was greater in the case of the sonic booms, about 10 dB for doubling.

By relating the reproduced noise levels to their original values it was concluded, with some reservations due to the experimental limitations, that the upper limit of acceptable sonic booms (as heard in domestic interiors) is about 1.9 psf initial pressure jump measured on the ground in the open. This figure is based on the value of 110 PNdB as the acceptable limit for conventional aircraft sounds.

In a later investigation (see capsule summary HRSC-10) Pearsons and Kryter obtained results very similar to those of the present study. The simulated sonic booms of that investigation were of a much better quality than those of the present experiment, however.

This is a significant paper in that this was one of the earliest attempts to establish an acceptability criterion for sonic booms.

HRSC-9
COMMUNITY REACTIONS TO SONIC BOOMS IN THE OKLAHOMA CITY AREA
Paul N. Borsky
Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, AMRL-TR-65-37, Vol. I, February 1965

This report presents the results of a public opinion survey conducted in conjunction with the Oklahoma City sonic boom tests of 1964. In these tests a total of 1253 sonic booms were generated in the Oklahoma City area over a period of six months, from February to July 1964. The intensity of the booms was scheduled for 1.5 psf for most of the study and for 2.0 psf during the latter stage. Atmospheric conditions and other practical problems, however, tended to reduce somewhat the actual average intensities of the booms under the flight track to 1.13 during the first 11 weeks, 1.23 psf during the next eight weeks, and to 1.60 psf during the final seven weeks of the program.

Almost 3000 adults representing a scientifically selected cross-section of local residents were personally interviewed three times during the six-month period to determine their reactions to the sonic booms. In addition, careful records were kept of all complaints received by the local Federal Aviation Agency representatives. The analyses of these representative interviews and local records are included in this report.

Volume II of this report (see capsule summary HRSC-14) presents the data obtained in this investigation in much more depth than the present volume. The analysis of the data is also much more extensive in Volume II. The reader is referred to the capsule summary of Volume II for a summary of the conclusions reached as a result of this investigation.

HRSC-10
LABORATORY TESTS OF SUBJECTIVE REACTIONS TO SONIC BOOM
K. S. Pearsons and K. D. Kryter
NASA CR-187, March 1965

The results of a laboratory test whose purpose was to investigate subjective reactions to sonic booms are presented in this paper. Subjects compared, in a special laboratory chamber, the subjective acceptability or noisiness of sonic booms (simulated) that would be heard outdoors and indoors with the sound of subsonic jet aircraft and bands of filtered white noise. The subjective acceptability of the booms was expressed in terms of equivalent perceived noise level in PNdB. (The use of this procedure was not meant to imply that a "PNdB" value can, or should, be calculated for a sonic boom; the PNdB values used refer to the calculated peak perceived noise level of the flyover sound of a subsonic jet aircraft that is judged to be subjectively as acceptable as a given sonic boom.)

The simulation facility used in these tests is described in capsule summary SM-1.

The 20 subjects for these tests consisted of 12 college students, 2 engineers, 2 technicians, an architect, 2 housewives, and an artist. Their median age was 21, and they consisted of an equal number of males and females. Each subject's hearing was tested and found to be normal.

The outdoor booms used in the tests were essentially N-waves. As measured inside the chamber, they had durations of 150 milliseconds and peak overpressures of $4 lb/ft^2$ and $2.3 lb/ft^2$.

For comparison with the sonic booms, three stimuli were chosen. Two were recordings of aircraft flyovers near takeoff while the third was a 1/3 octave band of noise with a 2 second rise time (the time from a level 20 dB below peak, to start of peak level), a 2 second duration, and a 2 second decay time (the time from end of peak level to a level 20 dB below the peak).

During the testing sessions each subject was asked to adjust the sound level of the comparison noise until, in his opinion, it was just as acceptable as the standard.

In another aspect of the experiment an electrocardiograph was used to monitor the subject's heart during a session in which he was exposed (with no foreknowledge that it would happen) to ten sonic booms over a period of ten minutes while listening to relaxing music. The purpose of this experiment was to investigate the startle effect of the booms and to determine how well the sub-

jects become accustomed to the repeated booms.

As a result of this investigation the following conclusions were reached:

1. A sonic boom of 2.3 lb/ft^2 measured outdoors may, in real life, be found generally objectionable when heard indoors inasmuch as:

   (a) the laboratory tests showed that a 2.3 lb/ft^2 boom, measured outdoors but heard indoors, would be equivalent in acceptability to the sound heard indoors of a subsonic aircraft flyover measuring about 113 PNdB outdoors or about 98 PNdB if measured indoors; and

   (b) the sounds of conventional aircraft at 110-112 PNdB outdoors (measuring 97 PNdB indoors) are generally thought to be near the upper limit of tolerable noise levels and are the levels experienced by people who are situated no more than 2-3 miles from the runway (4-5 miles from start of takeoff) of a commercial airport and directly, or nearly so, under the flight path.

2. A sonic boom of 2.3 lb/ft^2 measured outdoors will probably not be generally objectionable in real life when heard outdoors inasmuch as:

   (a) in the laboratory tests, the subjects judged a sonic boom having a peak overpressure of 2.3 lb/ft^2 to be equivalent to the sound of a subsonic aircraft at 95.5 PNdB.

   (b) 95.5 PNdB heard outdoors is thought to be tolerable inasmuch as this is considerably less than the 112 PNdB now experienced by some people near airports.

3. Startle reactions to sonic booms will probably not be a significant factor as a cause of annoyance with repeated regular exposures to sonic booms having outdoor peak overpressures of at least 2.3 lb/ft^2 inasmuch as this study, as have others, shows that man adapts both physiologically and psychologically with repeated exposure to sounds of this intensity.

Broadbent and Robinson (see capsule summary HRSC-8) conducted a study that was very similar to the present one. They found that a sonic boom recorded indoors and having an outdoor peak overpressure of 1.9 lb/ft^2 would be judged to be equally annoying as the sound of a subsonic jet or piston aircraft at 98 PNdB. It is pointed out in the present report that adjusting the peak overpressures in the two studies to be equal would result in equal PNdB values. The agreement between the results of the two studies indicates that these results have some validity.

This was an excellent investigation, providing several significant contributions to the state of knowledge concerning acceptable sonic boom overpressure levels produced by N-wave shaped signatures.

HRSC-11

OKLAHOMA CITY SONIC BOOM STUDY; FINAL PROGRAM SUMMARY

Federal Aviation Agency, Report No. SST 65-3, March 17, 1965

This publication provides a final summary of the Oklahoma City program in all of its aspects. As integral elements in the Oklahoma City program, (1) precise measurements of sonic boom overpressures in various geographical locations were recorded and analyzed (see capsule summary S-15), (2) meteorological effects on sonic boom were studied (see capsule summary P-42), (3) nine test houses in different parts of the boom area, and two test houses outside the boom area, were rented for instrumentation and observation as "control" structures (see capsule summary SR-12), and (4) a public opinion survey was conducted (see capsule summary HRSC-14).

The reader is referred to the capsule summaries above for details of the studies conducted in each of these areas.

In the present paper a brief description of the investigations conducted in each of the four areas is presented. The bulk of the paper, however, discusses the manner in which claims for sonic boom damages were handled. The claims procedure was as follows:

1. Statutory authority for the settlement of claims for damage arising from the noncombat activity of the Air Force, such as from the sonic booms generated by Air Force aircraft participating in the boom flights over the Oklahoma City area, is contained in Section 2733, Title 10, United States Code. This law was implemented through appropriate directives which provide for presenting and processing such claims.

2. Damage claim files sent to Tinker Air Force Base were in each instance reviewed by claims officers experienced in the adjudication of sonic boom claims. Final action was taken at that office on claims of $1,000 or less, all others being forwarded to Headquarters, United States Air Force, Washington, D. C., where claims of $5,000 or less were acted upon by the Judge Advocate General, United States Air Force.

3. All appeals from adverse decisions on these claims were acted on by the Secretary of the Air Force.

4. The basis upon which claims were paid included (1) eyewitness reports, (2) recognition of possible "triggering" effect of sonic boom overpressures, and (3) absence of engineering evidence that the boom did not cause the damage.

5. A large majority of disapproved claims alleged that plaster or sheetrock cracks in walls and ceilings were caused by sonic booms. Only in those cases where a professional engineer unequivocably stated that none of the damage resulted from sonic booms was disapproval action taken.

6. In evaluating plaster and sheetrock damage claims, (1) the engineers report, (2) other complaints of damage from the same geographical area, (3) such circumstances as the freshness of the cracks, the presence or absence of plaster dust or particles, and (4) the age and condition of the building were all thoroughly considered.

7. When it was determined the pre-existing plaster and sheetrock defects were aggravated by an Air Force-generated sonic boom, the award reflected appreciation and improvement resulting from repair.

8. Every effort was exerted to insure that just and reasonable decisions were made on these claims within the authority granted the Air Force.

The value of this paper lies mainly in its description of the claims procedure used in the Oklahoma City tests.

HRSC-12
HUMAN RESPONSES TO SONIC BOOM
Charles W. Nixon
Aerospace Medicine, Vol. 36, No. 5, May 1965, pp. 399-405

This paper summarizes some of the data obtained in various sonic boom tests of the early 1960's including the St. Louis tests of 1961-62 (see capsule summary HRSC-15) but not including the Oklahoma City tests of 1964 (see capsule summary HRSC-9). These data are summarized in terms of the nature of human responses and the manner in which they occur, factors influencing acceptance of the boom, the possibility of physiological injury, psychological effects, and some reports of alleged minor damage to property and their relation to human reactions.

Based upon this summary the following conclusions, which are of a preliminary nature, were reached:

1. No evidence has been obtained to suggest direct personal injury resulting from the sonic boom. Substantial evidence shows that no direct injury has been reported, even in response to sonic boom exposures many times greater than those experienced by typical communities.
2. Psychological reactions of individuals are not predictive due to large variations in the stimulus, the immediate environment and the att..udinal variables which may be related or unrel... the boom experience.

3. The com... ..y reaction pattern proceeds from a high initial negative response or objection to a level of accommodation and acceptance where it may remain indefinitely provided no unusual exposure occurs.

4. Currently the most promising approach to the operations problem is that of controlling flight profiles of supersoni^ missions in terms of increased altitudes and care in acceleration and maneuvers.

This is a good general review of the state of knowledge of human response to sonic boom just prior to the publication of the results of the Oklahoma City sonic boom tests.

HRSC-13
ON NOISE AND VIBRATION EXPOSURE CRITERIA
Henning E. von Gierke
Archives of Environmental Health, Vol. II, September 1965, pp. 327-339

This paper presents a discussion of noise and vibration exposure criteria. It compares the status of noise exposure criteria with the related field of vibration exposure. The portion of the report dealing with sonic booms is very brief. It is pointed out that none of the response criteria discussed elsewhere in the report can be meaningfully applied to the evaluation of sonic boom effects. No damage to hearing or any other harmful physiological effect has been found to be attributable to exposure to pressure waves of the magnitude experienced by communities. Disregarding the brief startle response (which, it is hypothesized, might to some degree be modified by adaptation to a regular supersonic transport schedule), it is concluded that there is hardly any noteworthy interference with with most tasks or job proficiencies. The discussion concludes with a warning that sonic boom criteria resulting from community response studies must be taken for what they are: neither medical safety criteria nor task interference criteria, but expressions of the majority of a population showing that it is willing to complain and act against such noise intrusion into their personal lives.

HRSC-14
COMMUNITY RESPONSE TO SONIC BOOMS IN THE OKLAHOMA CITY AREA; VOL. II. DATA ON COMMUNITY REACTIONS AND INTERPRETA^ ..S
Paul N. Borsky
Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, AMRL-TR-65-37, Vol. II., October 1965

This is an in-depth report on the resu... of a public opinion survey conducted in conjunction with the Oklahoma City sonic boom tests of 1964. Volume I of this report (see capsule summary HR-5) is similar to Volume II except that instead of presenting all of the data it only presents a summary of the data. Also, a much more extensive interpretation of the data is made in Volume II than was made in Volume I.

In the sonic booms tests discussed here a total of 1253 sonic booms were generated in the Oklahoma City area over a period of six months, from February to July 1964. The intensity of the booms was scheduled for 1.5 psf for most of the study and for 2.0 psf during the latter stage. Atmospheric conditions and other practical problems, however, tended to reduce somewhat the actual average intensities of the booms under the flight track to 1.13 during the first 11 weeks, 1.23 psf during the next eight weeks, and to 1.60 psf during the final seven weeks of the program.

Almost 3000 adults representing a scientifically selected cross-section of local residents were personally interviewed three times during the six-month period to determine their reactions to the sonic booms. In addition, careful records were kept of all complaints received by the local Federal Aviation Agency representatives. The data gathered from these interviews and records are presented in

detail along with an analysis of the trends indicated by these data.

The following conclusions were reached as a result of the analysis of this data:

1. Almost all residents (94%) reported that sonic booms caused house rattles and vibrations. Other sonic boom interferences with living activities were: being startled (38%): interruptions of sleep (18%), rest (17%), conversation (14%), and radio and TV (9%). Over half (54%) of all persons reported only house rattles or no interferences at all. Persons with the most favorable views reported only 36% had rattles or no interferences, compared with 73% of those with the most hostile views--a range of 37%.

2. More than a little annoyance with sonic boom interference increased from 37% of all people during the first interview to 56% on the third interview. Most of the increase was due to more intense sonic boom exposure during the last six weeks of the study. On the third interview, 25% with the most favorable views reported more than a little annoyance with booms, compared to 76% for the most hostile group--a range in reactions of 51%.

3. About one-fifth of all residents felt they had sustained damages by the booms during the first and second interview periods. On the third interview, almost one-fourth reported such alleged damage. During the six-month test, 38% overall felt they had been damaged by the booms, with plaster cracks most frequently reported. Only 7% reported damages three times, 11% twice, and 20% only once. Only 25% of persons with the most favorable views reported damages, compared to 56% for the most hostile group.

4. Oklahoma City residents generally have a low general complaint potential. Only 24% even felt like writing or calling an official about a serious local problem, and less than half (10%) actually followed through and did call.

5. Only 22% of all residents felt like complaining about the sonic booms at the end of the study, and only 5% actually did. Those with the most favorable attitudes toward booms reported that only 3% ever felt like complaining about the booms and only 2% actually did. In contrast, 37% of the most hostile group felt like complaining and 12% actually did.

6. Widespread feelings of futility in complaining probably contributed to the low levels of complaint. Only 4% felt that complaining had a "very good" chance of reducing the booms, and another 10% felt that complaining had even a "good" chance of accomplishing something.

7. The vast majority of residents felt they could learn to live with sonic booms. Over 90% felt they could accept eight booms per day indefinitely on the first interview, and 73% felt this way at the end of the six-month period. About 92% of persons with the most favorable views said they could accept the booms at the end of the study compared to 57% of the most hostile group. Even 40% of the persons who actually complained to the FAA said they could probably learn to live with the booms.

8. The FAA public information program was very successful in reaching residents. About 75% knew the physical causes of sonic booms, 83% believed they could always recognize the boom, 82% were aware of the regular schedule, two-thirds knew the purposes of the boom test, and half knew the six-month duration of the test.

9. Most residents were favorably disposed toward the sonic boom test. Over half (52%) felt the local booms were absolutely necessary on the first interview, and 38% felt this way on the last interview. Almost three-fourths of all residents felt that aviation was extremely important to local welfare and two-thirds of all persons felt the development of the SST was necessary. About one-third of all residents had personal or family connections with the aviation industry.

10. Respondents who had personal or family connections with the aviation industry reported the same reactions as persons with no aviation connections.

11. Respondents who did not believe others should report their complaints about the booms even if annoyed by them, generally reported 10-20% less hostile reactions toward the booms. The exclusion of these potentially biased respondents from the computations of total area responses increased hostile sonic boom reactions by 2-5%.

12. Reactions of urban and rural residents to sonic booms were essentially the same.

13. The actual sonic boom overpressures experienced by Oklahoma City residents during the six-month test were generally less than the programmed levels. During the last six weeks of the test, however, over 60% of the booms equalled or exceeded 1.5 psf in the closest areas.

14. Answers to speculative types of questions suggest that fewer residents think they can accept night booms. More direct research on this problem is needed before firm findings can be made.

15. Persons who actually complained to the FAA were the most intensely annoyed and most hostile toward the SST. They were not chronic gripers and liked their areas as well as non-complainers. They were equally sensitive to noise in general, but reported 3-4 times more sonic boom interference, four times more annoyance, [illegible] times more desire to complain, and 3 times more damage by booms. They less often believed in the importance of aviation in general, the necessity of the SST, or the necessity of local booms. About 40% of the complainers, however, felt they could learn to live with eight sonic booms per day. Complainers were more often middle-aged females with older children, and smaller families.

They generally had more education and income, and more often had ties with the aviation industry.

This was the most extensive community response flight-test program ever conducted. The results of this test continue to be used and referred to to the present day.

HRSC-15

RESULTS OF USAF-NASA-FAA FLIGHT TEST PROGRAM TO STUDY COMMUNITY RESPONSE TO SONIC BOOM IN THE ST. LOUIS AREA

Charles W. Nixon and Harvey H. Hubbard

NASA TND-2705, 1965

In this report data are presented from a series of community-reaction flight-test experiments in which the population of St. Louis, Missouri was repeatedly exposed to sonic booms in a range of overpressures up to about 3.1 psf. Results include those obtained from direct interviews, analyses of complaint files, and engineering evaluations of reported damage. These results are correlated with information on aircraft operations and sonic boom pressure measurements. Only the results concerning human response will be summarized here. For a discussion of the results concerning structural response the reader is referred to capsule summary SR-22.

There were some carefully monitored special flights during the test period as well as several unmonitored flights previous to the test period. The first flight was made in July 1961, and up to the time of the community response study, at least 34 flights were known to have been made. Thirteen special flights of B-58 and F-106 aircraft were made in a selected corridor which passed along the edge of the main urban area of greater St. Louis at various times of day and night during a six-day period beginning November 7. Subsequent to these special flights, 29 others were known to have been made. Four of these, which occurred on January 3, 1962 and January 6, 1962, were also special flights at a relatively lower altitude and with higher associated sonic boom pressures. A total of 76 supersonic flights was thus known to have been made in the test area during a 7-month period.

Immediately following the initial series of special flights, approximately 100 households were interviewed at each of 10 sampled areas. The initial respondent contact consisted of a detailed intensive interview of 1 to 1-1/2 hours duration. The interview did not reveal the purpose of the study but was described to the respondent as a broad community survey of how people felt about the communities in which they live. The background and personal characteristics of the respondents were recorded, as well as complaint potential, experiences, and attitudes toward the community, toward commercial and military aviation and other related basic variables. Respondents were told that the survey would continue for several weeks and that the interviewer might call back to obtain additional information.

Approximately 2 weeks following completion of the initial interviews, the second series of special supersonic flights was made over the same ground track. These four flights were scheduled to provide fewer but more intense booms than were experienced during the first test exposure. Call-back and control interviews were begun within 2 days. A total of 1,043 respondents completed both the interview and re-interview and 298 control interviews were also completed.

The following conclusions were reached as a result of this investigation:

1. The personal interview studies indicated that after 66 supersonic flights, about 90 percent of those contacted experienced some interferences as a result of sonic booms, about [illegible] percent were annoyed by them, less than 10 percent had contemplated complaint action, and a fraction of 1 percent had actually filed a formal complaint.

2. The cumulative total of complaints recorded was approximately proportional to the number of supersonic missions. A large percentage of recorded complaints made some mention of building damage. There were no direct adverse physiological effects.

This was one of the earliest community response surveys to be conducted in conjunction with a controlled flight-test program. The later Oklahoma City sonic boom tests were much more extensive (see capsule summary HRSC-14), however.

HRSC-16

THE LOUDNESS OF SONIC BOOMS AND OTHER IMPULSIVE SOUNDS

E. E. Zepler and J. R. P. Harel

Journal of Sound and Vibration, Vol. 2, No. 3, 1965, pp. 249-256

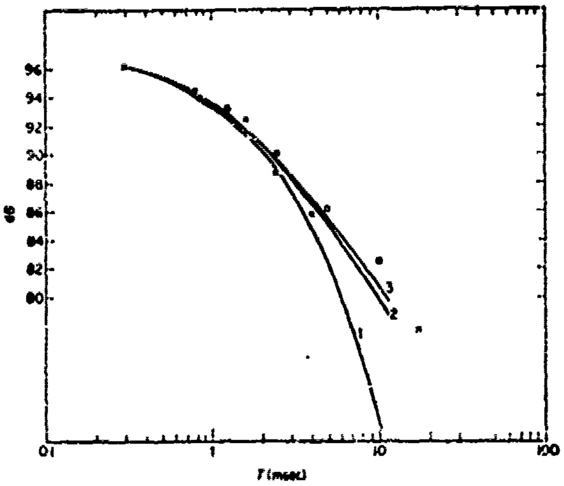
In this paper the loudness of sonic booms and other impulsive sounds are subjectively evaluated. A pair of earphones was developed for this purpose. The frequency response of these earphones was practically flat between zero frequency and 1500 cps. The cavity had a volume of 80 cm^3 and the maximum pressure obtainable was approximately 2 psf. The comparatively large cavity was chosen to minimize differences in pressure due to different ear cavities of subjects and also to reduce the effect of air leakage.

As comparison signal in determining the loudness of a given signal, a tone of 400 cps was chosen. To use a steady tone rather than some transient signal had the advantage that the source of reference was known and well defined. It had the disadvantage that the signals to be compared were so different that it was extremely difficult to decide on equal loudness. This necessitated the use of a fairly large number of subjects.

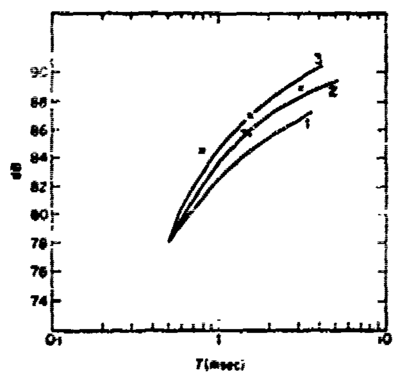
In the first series of tests about seventy subjects were employed. The N-wave and the 400 cps tone were alternately applied to the earphones and the strength of the tone was adjusted until it was judged to be equal in loudness to the N-wave. The results differed considerably between different subjects, but individual subjects were usually consistent within a few dB if due care was taken concerning the fit of the earphones.

The main results are shown in the two figures below which were taken from this paper. The first figure shows that, when the maximum pressure of the N-wave is held constant, the loudness decreases as rise time increases. The second figures shows that, when the rise rate

is held constant, the loudness increases as the maximum pressure increases. It can be seen that for rise times larger than 1 msec, variations in rise time, with constant maximum pressure, has more effect than a corresponding variation in maximum pressure with constant rise rate.



Loudness versus rise time with constant maximum pressure
Experimental results· ▫ ; X



Loudness versus rise time with constant rise rate
Experimental results· X, theoretical curves. 1, 2, 3

The effect of filters on loudness was measured for N-waves with rise times of 1 msec and 3 msec, respectively. Cutting off below 20 cps or 40 cps had practically no effect in either case while cut-off below 240 cps caused a drop of about 5 dB.

In the second part of the paper an attempt is made to explain the results in light of Fourier analysis. Curves are drawn of $k[F(\omega)]^2$ where $F(\omega)$ is the Fourier transform of the impulsive signal and k is a weighting factor. The areas under the curves giving the weighted energies were compared with subjective loudness. Agreement between the two was found to be good. As a result, it is concluded that the loudness of impulsive signals of short duration and similar frequency density function is proportional to the weighted energy. The results also suggested that the loudness of an impulsive signal in which the energy is concentrated essentially in one frequency is considerably louder than an impulsive signal of equal weighted energy but of a wide frequency spectrum.

This is a very significant paper in that the theory developed here for calculating the loudness of sonic booms formed the basis for most subsequent theories.

HRSC-17
COMMUNITY REACTIONS TO SONIC BOOMS IN THE OKLAHOMA CITY AREA; VOLUME III. QUESTIONNAIRES (APPENDIX TO VOLUME II)
Paul N. Borsky
Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio, Report No. AMRL-TR-65-37, March 1966

This is the appendix to Volume II (see capsule summary HRSC-14) of this report. It contains samples of questionnaires used during the interviews that took place from February to July 1964 in the Oklahoma City, Oklahoma area. That area was repeatedly exposed to sonic booms generated to simulate overpressure levels that would be expected for supersonic transport overflights. The schedule provided for eight booms per day. During the six-month period, almost 3,000 local residents were interviewed three times to determine the nature and extent of their reactions to the sonic booms. The reader is referred to capsule summaries HRSC-9 and HRSC-14 for details of this investigation.

HRSC-18
AN INVESTIGATION OF THE EFFECT OF BANGS ON THE SUBJECTIVE REACTION OF A COMMUNITY
D. P. B. Webb and C. H. E. Warren
Royal Aircraft Establishment Technical Report No. 66072, March 1966

This report describes a field experiment on the effects of sonic booms on a community, conducted under the code name Exercise Yellowhammer. The objective of the experiment was to investigate the subjective reactions of a community as sonic booms became an established feature of the environment. Simulated sonic booms were made by firing explosive charges which were suspended from a balloon in the vicinity of the community. At suitable intervals the number of booms per day, the intensity of the booms, and the diurnal times at which the booms were made were sepa .tely varied.

The program of booms was spread over a period of fourteen consecutive weeks. The booms took place chiefly on Monday and Tuesday of each week. On each firing day for the first five weeks the community was subjected to a standard series of booms, nominally twenty-four in number and of a given intensity, and spread randomly throughout the day between about 0930 and 1530 hr. During the remaining nine weeks the number, intensity, and times of the booms were separately varied at intervals which phased with the interviewing of four samples into which the community was divided.

The waveforms produced by the explosives resembled distorted N-waves. The average peak overpressures experienced by the community varied from about 1.4 psf to 5.1 psf. The duration of the positive phase of the booms varied from about 5.7 milliseconds to about 11.3 milliseconds.

The community consisted of some 280 people engaged in common everyday occupations. The community was divided into four samples roughly equivalent in size, sex, and age structure, and the subjective reaction of the community was assessed by interviewing these samples in turn on Thursday and Friday of each week of the period of the exercise.

The following conclusions were reached as a result of this investigation:

1. The percentage of persons annoyed by booms became less as the booms became an established feature of the environment.

2. Nothing could be convincingly discerned in regard to the effects of sex, age, and occupation upon subjective reaction.

3. The community reacted significantly both to an increase in the frequency of the booms and to an increase in the intensity. The effects of other variations introduced were not of discernible significance statistically.

In another community response study (see capsule summary HRSC-19) a significant relationship was found between the subjective response to sonic booms and sociological variables, in contrast to the results of the present investigation. The Oklahoma City results (see capsule summary HRSC-14) also showed such a relationship.

HRSC-19
OPINION STUDY ON THE SONIC BANG
Medicin Lt.-Colonel de Brisson
Royal Aircraft Establishment Library Translation No. 1159, April 1966

This report presents the results of a public opinion study of the reactions to the sonic boom by the populations in the East and South-West of France where there had been appreciable supersonic flying over the previous few years. The survey investigated the population's sensitivity to the sonic boom as affected by geographical, sociological, and attitudinal variables.

The number of questionnaires completed and analyzed was 2296. Seventy-seven investigators participated in the inquiry in 704 different localities. The interviews lasted from 25 to 45 minutes.

From the data obtained in the survey, the following broad characteristics were sorted out:

1. The most unexpected result was the importance of sociological factor, while the geographical and living area factors (which it is admitted were very poorly checked from the point of view of exposure to the sonic boom and surrounding noise) did not appear decisive. It was found, however, that tolerance to sonic bangs was low in small towns.

2. It was found that married women are particularly sensitive to the sonic boom and hostile to progress in aviation, while unmarried men were the most tolerant in this respect.

3. Sensitivity to the sonic boom and disapproval of progress in supersonic aviation were found to increase with age.

4. It was found that people with a high educational level, although sensitive to noise, tend to minimize their sensitivity to the sonic boom because they accept the development of supersonic aviation as an actuality while people with a low educational level, although insensitive to noise, in general are opposed to all notions of progress in aviation and display more sensitivity to the sonic boom.

5. A study of the sensitivity to sonic boom variable as a function of income and occupation showed a close relationship parallel to that of the educational level.

In another investigation concerning community response to sonic booms (see capsule summary HRSC-18) Webb and Warren found no conclusive relationship between sociological variables and response to sonic booms. On the other hand, the results of the Oklahoma City sonic boom tests (see capsule summary HRSC-14) showed that people who complained about the sonic booms were more often middle-aged females, with older children, and smaller families. Those results tend to support the findings of the present investigation. However, the Oklahoma City results also showed that these same middle-aged female complainers generally had more education and income than the non-complainers, in contrast to the findings of the present investigation.

HRSC-20
SONIC BOOMS--GROUND DAMAGE--THEORIES OF RECOVERY
H. L. Kelley III
Journal of Air Law and Commerce, Vol. 32, Autumn, 1966, pp. 596-606

In this article a discussion of the legal basis for making sonic boom damage claims is presented. It is stated that damage may be covered by the "all risk," "aircraft damage," or "explosion" coverages of insurance policies, or the Federal Tort Claims Act in cases involving military aircraft.

It is argued that strict liability should be found applicable against the airlines in the case of damaging sonic booms for two reasons. First, the operation of supersonic aircraft will cause some damage which cannot be eliminated by the exercise of the utmost care, and it therefore should be treated as an ultrahazardous activity. Secondly, sonic booms involve the same phenomena and effects as do concussions from blasting; therefore, the blasting laws should apply.

A much more extensive review of the legal aspects of sonic booms was given in the papers summarized in capsule summaries HRSC-59 and HRSC-64.

HRSC-21
EFFECTS OF SONIC BOOM ON PEOPLE: REVIEW AND OUTLOOK
Henning E. von Gierke
Proceedings of the Sonic Boom Symposium, The Journal of the Acoustical Society of America, Vol. 39, No. 5, Part 2, 1966, pp. S43-S50

This paper presents a review of research conducted up to 1965 concerning the effects of sonic booms on people. The review is very general and does not go into very much depth. However, it does give a good overview of the various studies that have been conducted and the range of overpressures involved in each. A brief discussion is also given of observed and predicted auditory responses to sonic booms. This discussion is summarized by the table below, which was taken from this paper.

Nature of Auditory Response	Sonic-Boom Experience or Prediction
Rupture of the tympanic membrane	None expected below 720 lb/sq ft None observed up to 144 lb/sq ft
Aural pain	None observed up to 144 lb/sq ft
Short temporary fullness, tinnitus	Reported above 95 lb/sq ft
Hearing loss permanent	None expected from frequency and intensity of boom occurrence
Hearing loss temporary	None measured (1) 3-4 h after exposure up to 120 lb/sq ft (2) immediately after boom up to 10 lb/sq ft
Stapedectomy	No ill effects reported after booms up to 3.5 lb/sq ft
Hearing aids	No ill effects reported after booms up to 3.5 lb/sq ft

Auditory response to sonic booms

HRSC-22

LABORATORY TESTS OF PHYSIOLOGICAL-PSYCHOLOGICAL REACTIONS TO SONIC BOOMS

K. D. Kryter

Proceedings of the Sonic Boom Symposium, The Journal of the Acoustical Society of America, Vol. 39, No. 5, Part 2, 1966, pp. S65-S72

In this paper the methods and results of laboratory investigations conducted up to 1965 concerning physiological-psychological reactions of humans to sonic booms are discussed. The studies summarized here include those of Zepler and Harel (see capsule summary HRSC-16), Richards (see capsule summary HRSC-6), Broadbent and Robinson (see capsule summary HRSC-8), Pearsons and Kryter (see capsule summary HRSC-10), and others of lesser significance.

The following conclusions were reached as a result of this review:

1. The basic audibility and perceived noisiness of N-waves or sonic booms of modest intensities may be understandable or predicted from a knowledge of their physical characteristics.

2. The sounds heard in a house subjected to a sonic boom are judged to be noisier or more unwanted than the sonic boom heard outdoors, probably because of rattles and other secondary sounds that result from vibration of the house.

3. The sonic boom, as heard indoors, at levels anticipated for future supersonic commercial aircraft would appear to be about equally acceptable as the sound presently heard indoors directly under the flightpath of subsonic jet aircraft at an altitude of 15[illegible] feet following takeoff.

4. It seems possible that startle reactions to sonic booms would adapt or cease upon repeated exposure to sonic booms of typical anticipated levels.

5. The arousal effects of sonic booms when a person is asleep is a moot subject, particularly with respect to the question of adaptation.

6. The conclusions and speculations concerning the effects of sonic booms in this paper pertain only to the effects of booms having peak overpressures of the order of about 2.0 lb/ft².

This is a very good summary of the state of knowledge concerning human response to sonic booms as of 1965.

HRSC-23

EFFECTS OF SONIC BOOM ON PEOPLE: ST. LOUIS, MISSOURI, 1961-1962

Charles W. Nixon and Paul N. Borsky

Proceedings of the Sonic Boom Symposium, The Journal of the Acoustical Society of America, Vol. 39, No. 5, Part 2, 1966, pp. S51-S58

A review of the study made in St. Louis, Missouri during a 10-month period from July 1961 to April 1962 is presented in this paper. The purpose of this study was to investigate community response to sonic booms. The review given in the present paper contains no information not contained in the earlier reports on this study. The reader is referred to capsule summaries HRSC-15 and HRSC-12 for information on the St. Louis sonic boom tests.

HRSC-24

THE INFLUENCE OF IMPULSE NOISE CREATED BY MODERN AIRPLANES ON THE HUMAN ORGANISM

A. V. Chapek, B. N. M[illegible]tsoyev, and U. N. Somonov

From Problems in Aerospace Medicine. Translation of a Russian-language book entitled "Problemy Kosmicheskoy Meditsiny: Materialy Konferentsii 24-27 Maya 1966," edited by V. V. Parin, Joint Publications Research Service: 38, 272, October [illegible], pp. 499-500

[illegible] article presents the results of an experiment concerning the physiology of human [illegible] sonic booms. More than 150 investigations were [illegible] using engineers and doctors [illegible] at an observation point under the flight path of an aircraft flying at supersonic speeds. The following characteristics [illegible] were investigated:

The [illegible] potentials of the brain (EEG), the [illegible] system with recording of an [illegible] and of arterial pressure, and [illegible] of the activity when [illegible] intervals of time (before [illegible] after a sonic boom).

[illegible] (adaptometry), electrical [illegible] the visual analyzer, duration [illegible] period of the visual sequence [illegible], and corticosteroids [illegible] blood (before and after [illegible] boom)

Also, a questionnaire was used to interrogate the population of a city located under the flight trajectory.

The following conclusions were reached as a result of this investigation:

1. A sonic boom of intensity 1.72 psf caused brief shifts of certain physiological functions: quickening of the pulse (within the range of 10 to 46 beats per minute) and lowering of the alfa rhythm of the EEG. These changes did not exceed the limits of physiological fluctuations and returned rather rapidly (in 1-2 minutes) to the initial level.

2. The biopotentials of the heart, the sharpness of hearing, the duration of the subsequent visual image and of its latent period, and of the corticosteroids of the blood after the action of a boom of 1.72 psf intensity did not change significantly in comparison with the background data.

3. The quality of the activity connected with the estimation of microintervals of time at the moment of the action of a boom dropped slightly and then quickly returned to the initial level.

4. Booms of an intensity up to 1.54 psf did not cause any shifts of physiological functions in the test subjects.

5. The sonic booms had, based on the questionnaire data, the following effects on persons located under the flight trajectory: strong irritating action--in 38% of the cases, average action--in 28% of the cases; weak action--in 6.8% of the cases; no irritation in 27.2% of the cases of people who were questioned. For persons subjected to the repeated action of impulse noises the latter had a strong irritating effect in only 3.6% of the cases; an average effect in 29.3%; and a weak effect in 20.8%; in 46.3% of the cases booms did not have any effect at all.

6. It was concluded that many people adapt to the effects of impulse noise and do not experience a negative effect from it.

This is one of the few articles available describing research that has taken place in Russia concerning human response to sonic booms.

HRSC-25
EFFECTS OF SONIC BOOMS ON THE PUBLIC
S. Chevallier and J. Perrochon
NASA TT F-10,709, January 1967

The purpose of the investigation discussed in this paper was to determine the maximum overpressure for an N-wave type sonic signature boom which is statistically acceptable over a short period of time without distress to the public. In order to accomplish this, part of the personnel of the Flight Testing Center at Bretigny, France, were exposed to 50 simulated sonic booms and three actual sonic booms generated by a Mirage III over a period of 7 days of testing. The simulated sonic booms were produced by explosive charges. At the end of the testing period questionnaires were distributed to the personnel who had been exposed to the booms. About 600 completed questionnaires were received. The following conclusions were based upon the results obtained from the questionnaires:

1. It was found that the influence of exposure (orientation of the building, window open or closed, etc.) was minor and, in any event, undetectable in terms of its effect on the responses of the subjects.

2. The following conclusions were reached in regard to the acceptability of various overpressures:

   a) not bothersome: pressure variation of about 1 psf

   b) slightly bothersome: pressure variation of about 1.3 psf

   c) annoying but not painful: pressure variation of about 1.5 psf

   d) painful: pressure variation of abou 1.7 psf

   e) very painful: pressure variation of about 2.1 psf.

The above findings do not agree with the results obtained by Pearsons and Kryter (see capsule summary HRSC-10) and by Broadbent and Robinson (see capsule summary HRSC-8) in laboratory tests involving exposure of subjects to simulated sonic booms. Both of those investigations found that the upper limit of acceptability for sonic booms heard outdoors is about 2.3 psf. The disagreement in results might be due to the poor quality of the simulated sonic booms of the present investigation, which, according to opinions repeatedly expressed, were less disturbing, assuming the same intensity, than real booms.

HRSC-26
FARFIELD SPECTRUM OF THE SONIC BOOM
Walton L. Howes
Letter to the editor, Journal of the Acoustical Society of America, Vol. 41, No. 3, Mar 1967, pp. 716-7

This short note presents a correction to the pressure spectrum formula derived by Zepler and Harel (see capsule summary HRSC-16) for an N-wave. The spectrum given by Zepler and Harel for an N-wave having unit amplitude is

$$P(\omega) = \sin x/(\omega x)$$

where $P(\omega)$ is the Fourier transform of the pressure amplitude $P(t)$

$$x = \omega T/2$$
and T = period of N-wave

It is shown in the present paper that the above formula is incomplete, and that the correct formula for the pressure spectrum of an N-wave is given by

$$P(\omega) = (2\pi)^{-1/2} T\, P(T)\ [(\sin x/x^2) - (\cos x/x)]$$

$$= (2\pi)^{-1/2} T\ P(T)\ j_i(x)$$

where $j_i(x)$ is a spherical Bessel function of the first kind and order.

HRSC-27

AN INVESTIGATION OF THE WAVEFORM CHARACTERISTICS AND SUBJECTIVE EFFECTS OF SONIC AND EXPLOSIVE BANGS

C. H. E. Warren and T. A. Holbeche

Royal Aircraft Establishment Technical Report 67167, July 1967

This report describes some experiments that were done to gain some preliminary information on the waveform characteristics and on the subjective effects of sonic booms. A series of carefully controlled flights by an aircraft at supersonic speeds was made in an exercise known as Exercise Crackerjack. Overpressures in the 0.5 - 3.0 psf range were generated by these flights. The subjects exposed to these booms were asked to give their reactions and also to compare the sonic booms with explosive bangs. Also studied was the ability of people to distinguish between sonic booms and bangs generated by explosives when experienced indoors.

The results obtained concerning subjective response to sonic booms show that tolerance to booms of a given overpressure decreases with increasing frequency. They also show that most subjects felt that they would be much less tolerant to night-time sonic booms. The indication is that sonic booms having a pressure rise of about 1.5 psf may be tolerable, whereas those around 2-1/2 psf are becoming objectionable.

The discrimination study resulted in the conclusion that bangs made by the firing of pairs of explosive charges with the appropriate spacing in time are indistinguishable from aircraft sonic booms when heard indoors.

The results of this test show better agreement with those of Pearsons and Kryter (see capsule summary HRSC-10) and Broadbent and Robinson (see capsule summary HRSC-8) than did the results found in the French experiment reported by Chavallier and Perrochon (see capsule summary HRSC-25). Pearsons and Kryter, and Broadbent and Robinson found the upper limit of acceptability of sonic boom overpressure to be about 1.9 psf, while the present experiment showed that overpressures of 2.5 psf were becoming objectionable and booms of 1.5 psf were tolerable. Thus the results of this experiment tend to qualitatively support those of Pearsons and Kryter and Broadbent and Robinson.

HRSC-28

PSYCHOLOGICAL EXPERIMENTS ON SONIC BOOMS

K. D. Kryter, P. J. Johnson, and J. R. Young

Sonic Boom Experiments at Edwards Air Force Base, Interim Report, July 28, 1967, Annex F

The psychological experiments on sonic booms carried out as part of the Edwards Air Force Base sonic boom experiments are described in this report. The following three psychological experiments were conducted:

1. Paired-comparison tests and absolute ratings of the relative acceptability of sonic booms with the flyover noise from subsonic jet aircraft, the subjects being placed both outdoors and indoors during the tests.

2. Paired-comparison tests and absolute ratings of the relative acceptability of sonic booms from one type of supersonic aircraft to sonic booms from a second type, and of sonic booms from the same type of aircraft but flown under different operational conditions.

3. An attitude survey of the acceptability of the sonic booms to residents in a military community habitually exposed to sonic booms.

Subjects selected from residents of the communities of Edwards Air Force Base, Fontana, and Redlands, California were assigned to various indoor and outdoor test sites at Edwards Air Force Base. The aircraft overflights were made in pairs with approximately one to two minutes between the members of each pair and a minimum of approximately four to five minutes between pairs. The subjects' main task was to indicate on an answer sheet which sound of each pair was the more acceptable if heard in or near their homes. They were also required to rate on a 13-point scale the acceptability of each of the sonic booms or sounds heard on certain days.

The following is a summary of the results of these experiments:

1. When indoors, subjects from Edwards Air Force Base judged booms from the B-58 at 1.69 psf nominal peak overpressure outdoors to be as acceptable as the noise from a subsonic jet at an intensity of 109 PNdB measured outdoors.

2. When indoors, subjects from the towns of Fontana and Redlands judged the boom from the B-58 at 1.69 psf nominal peak overpressure outdoors to be as acceptable as the noise from a subsonic jet at an intensity of 118 to 119 PNdB measured outdoors.

3. The booms heard outdoors from the B-58 at 1.69 nominal peak overpressure were judged to be as acceptable as the noise heard outdoors from a subsonic jet at 105 PNdB, 111 PNdB, and 108 PNdB by subjects from Edwards Air Force Base, Fontana, and Redlands, respectively.

4. When indoors, 27 percent of the subjects from Edwards and 40 percent of the subjects from Fontana and Redlands combined rated the B-58 booms of nominal peak overpressure of 1.69 psf as being between less than "just acceptable" to "unacceptable."

5. When outdoors, 33 percent of the subjects from Edwards and 39 percent of the subjects from Fontana and Redlands, combined, rated the B-58 booms of nominal peak overpressure of 1.69 psf as being between less than "just acceptable" to "unacceptable."

6. Residents of Edwards Air Force Base who served as subjects had been in residence there for an average of two years and had been exposed during that period to about 4-8 booms per day of median nominal peak overpressure of 1.2 psf and to subsonic aircraft noise having peak PNdB levels of about 110 PNdB. The towns of Fontana and Redlands, on the other hand, were not under or near the flight track of supersonic aircraft and were occasionally exposed to noise of subsonic aircraft at a peak level of about 95-100 PNdB.

7. When of approximately equal nominal or measured peak overpressure and when heard indoors and judged against the aircraft noise, the boom from the XB-70 was slightly less acceptable than the booms from the F-104 or B-58 aircraft. When heard outdoors and judged against aircraft noise, the boom from the B-58 was slightly less acceptable than the booms from the XB-70 and F-104 aircraft.

8. When one type of boom was judged against another type of boom at equal nominal peak overpressure, no significant difference in their acceptability was measured in these tests.

9. The unacceptability of sonic booms, as a function of intensity, increases at about half again as fast a rate as does the unacceptability of the noise from subsonic aircraft; i.e., in terms of judged unacceptability, an increase of 10 PNdB in intensity of a noise from a subsonic aircraft was equivalent to about a 6 dB increase (from 1 psf to 2 psf) in the intensity of a sonic boom.

10. The results averaged over all tests indicates that the booms and particularly the noise were rated slightly more unacceptable by the listeners outdoors than by the listeners indoors. Also, the precision of the judgments and rate of growth of unacceptability as a function of the intensity of the booms or noise was about 50 percent greater for listeners outdoors than indoors.

11. On the average, two booms were judged to be significantly different in acceptability when their nominal or measured peak overpressures differed by about 1 dB, and by about 2 dB when the two booms were compared against a reference aircraft noise.

12. An attitude survey of residents (15 percent of whom served as subjects in these experiments) at Edwards Air Force Base revealed that 26 percent rated the boom environment as being between less than "just acceptable" to "unacceptable" for the month of June, when there was an average of about 10 booms per day at a median nominal peak overpressure of about 1.69 psf. Fourteen percent of the residents also rated the boom environment prior to June as being between less than "just acceptable" to "unacceptable." During this period there were about 4 to 8 booms per day at a median nominal boom level of 1.2 psf. Six percent rated the ambient daily aircraft noise and seven percent rated the street noise as being between less than "just acceptable" to "unacceptable."

13. Within the adult population studied, age and sex are not statistically significant factors in the ratings or paired-comparison of the unacceptability of sonic booms or the aircraft noises.

These conclusions show a definite trend toward greater acceptance of the sonic booms by the Edwards Air Force Base residents than by the residents of Fontana and Redlands. This indicates that a certain amount of adaptation to sonic booms does take place over an extended period of time.

This investigation and the community response survey conducted in conjunction with the Oklahoma City sonic boom tests are the most extensive and most-often-referred-to flight test investigations ever conducted concerning human response to sonic booms.

HRSC-29

ANALYSIS OF U. S. AIR FORCE SR-71 SONIC BOOM DAMAGE COMPLAINTS AND FLIGHT DATA

Thomas H. Higgins

Paper Presented to the Committee on SST-Sonic Boom NAS-NRC, November 13, 1967

A review of damage complaints, claims, and flight data associated with the sonic booms caused by U. S. Air Force SR-71 airplanes is presented in this paper. Flights were conducted near such major metropolitan areas as Chicago, Los Angeles, Dallas/Fort Worth, Minneapolis/St. Paul, New Orleans, Atlanta, Indianapolis, and Denver. The primary purpose of these flights was to demonstrate the operational suitability of the total SR-71 system.

The statistics showed that in the larger metropolitan areas, Chicago and Los Angeles, damage complaints per boom per million of the exposed population averaged approximately six. There was more variability and in general a lesser rate of damage complaints for those metropolitan areas with a total urban and rural population of approximately 1.5 million or less. The exact reasons for this could not be determined due to the lack of accurate flight track data.

A hypothesis to be tested is then proposed:

$$\bar{\Delta P} \geq N_m P_b P_d = \bar{\Delta P} \cdot 6 \cdot N_b (N_p/10^6)$$

where N_m = Number of material populations
N_b = Number of sonic booms
N_p = Number of people exposed
P_b = Probability of ΔP (reference 1 psf nominal)
P_d = Probability of material damage.
and $\bar{\Delta P}$ = Nominal calculated overpressure in pounds per square foot (psf) using a standard atmosphere.

This formula was based on the results of previous overflight programs in St. Louis and Oklahoma City and the number of damage complaints per boom per million population associated with those programs at time periods equivalent to the SR-71 program. Sufficiently accurate data was not

available for the SR-71 flights, however, to verify the hypothesis.

This is a good general summary of the sonic boom effects resulting from the SR-71 flight program.

HRSC-30
THE SUBJECTIVE EVALUATION OF SONIC BANGS
D. R. Johnson and D. W. Robinson
Acustica, Vol. 18, No. 5, 1967, pp. 241-258

An experiment is described in this paper in which 61 subjects used the method of direct magnitude estimation to judge the relative annoyance of sonic booms, explosions, and jet aircraft noise. Artificial white noises were included to test the subjects' performance for individual consistency and to compare their results with the established relationship between subjective magnitude and objective level.

A demonstration of sonic booms organized by the Ministry of Aviation and the Royal Air Force provided the opportunity to carry out the experiment. The flight program consisted of a series of four sonic booms with nominal peak overpressures ranging from about 1.5 psf to 2.3 psf and two low altitude full-power runs by a Comet jet aircraft planned to give a peak level of around 110 PNdB, the latter being included to provide a more familiar type of noise for purposes of comparison. These events followed one another about every five minutes and during the intervals a series of high explosive charges was detonated. The explosions were fired in pairs with a time delay between the detonations of about 100 ms, corresponding to the bow and stern shocks of the sonic booms.

The calibrating sounds consisted of a series of white noises of fixed spectral distribution but adjustable level, each presented for about 5 seconds.

Since the purpose of these was to test the quality of the subjects' performance at numerical annoyance estimation, an element of replication was built in; and by controlling the level the scale relation between annoyance and sound pressure level could be deduced for each individual and for the group.

The whole program was given twice, once in the morning and once in the afternoon. Thus, by dividing the subjects into two groups A and B it was possible to obtain two complete sets of outdoor and indoor results simply by exchanging locations after lunch.

The subjective tests were conducted in the following way. The first sound heard by the subjects was the white noise, presented at a level expected to lie within the range of annoyance of the other sounds. Subjects were instructed to consider the annoyance of this sound to be worth 10 units, and then to award every succeeding noise in the sequence a numerical score indicating how annoying it appeared to be, in relation to this initial sound. Thus if the second noise was judged to be twice as loud as the first noise it would merit a score of 20 on the test sheet. The subjects were not given the opportunity of hearing the reference sound again as such, and so from the first moment of the morning session the judgments throughout the day were made entirely in terms of the initial datum.

The results showed that the annoyance of sonic booms correlates closely with calculated loudness level, nearly as well with perceived noise level but poorly with peak overpressure. Conventional methods of calculation for steady sounds had to be modified to take account of the predominance of low frequency energy and of the short duration of sonic booms. The appropriate band pressure levels were derived from the Fourier transform of the waveform by averaging band energies over the auditory critical time of 70 ms. The same procedure was applied to explosions. The relative annoyance of the transient sounds and of the jet aircraft and white noise were then correctly predicted.

The subjective results showed that a peak overpressure of about 1.9 psf measured at ground level is about as annoying as jet noise at 110 PNdB, but only within a margin of 6 dB due to limitations of the sound reproducing equipment and psychological uncertainties resulting from the unnatural environment of the listeners.

The double explosions were intended to sound similar to the sonic bangs but in the absence of precise data to ensure this object they were arranged to have a similar range of peak overpressure. However, the spectrum peak of the explosions occurs at a higher frequency and largely for this reason they turned out to be much louder. It is concluded from this that, although it may be admissible for subjective purposes to rate sonic booms of similar waveform by peak overpressure, the latter is a useless measure for comparing transient sounds in general.

Judgments on door slams were included for general interest. The subjects found on the average that such a familiar event, even though slightly exaggerated for the occasion, was 29% more annoying than the sonic booms.

The finding here that a sonic boom overpressure of 1.9 psf was about as annoying as subsonic aircraft noise of 110 dB is in complete agreement with the results of an earlier laboratory investigation by Broadbent and Robinson (see capsule summary HRSC-8). The finding that annoyance of sonic booms correlates poorly with peak overpressure underscored the importance of considering all characteristics of the sonic boom pressure signature.

HRSC-31
ON SUPERSONIC VEHICLE SHAPES FOR REDUCING AUDITORY RESPONSE TO SONIC BOOMS
Walton L. Howes
NASA SP-147, Sonic Boom Research, 1967, pp. [illegible]

This paper is the same as that summarized in capsule summary HRSC-32. The reader is referred to that capsule summary for details of this work.

HRSC-32
ON SUPERSONIC VEHICLE SHAPES FOR REDUCING AUDITORY RESPONSE TO SONIC BOOMS
Walton L. Howes
NASA TMX-52294, 1967

This short paper discusses the design of supersonic vehicles to reduce auditory response to sonic booms. The method proposed is centered upon obtaining a signature which approximates one cycle of a sine wave. Such a signature would have most of its energy in the infrasonic range (frequencies below lower cut-off of the human ear) thus reducing auditory response to the boom.

Using Whitham's theory (see capsule summary G-3) and working backward from the desired signature, the required equivalent body shape is determined. The shape is found to resemble that of a low wave drag body.

Preliminary results for the selected F(y) and a nominal sea level overpressure of 1 pound per square foot for a body at 70,000 feet altitude indicated that a near field signature is not obtained beyond 20,000 feet from the craft even at the optimum Mach number M = 1.26 , which yielded the greatest extent of the near field. Here the near-field was defined as that region surrounding the craft for which the gradient of the pressure signature is positive immediately following the initial shock wave. For an overpressure of 0.5 pounds per square foot and other conditions unchanged, the near-field was found to extend beyond 70,000 feet.

It is tentatively concluded that the simultaneous achievement of overpressures greater than 1 psf and an extensive near field (to 70,000 feet as defined here) appears difficult.

This is a good paper in that it demonstrated that there are other methods of reducing human response to sonic booms than reducing the maximum overpressure.

HRSC-33
SONIC BOOM EFFECTS ON PEOPLE AND STRUCTURES
Harvey H. Hubbard and William H. Mayes
NASA SP-147, Sonic Boom Research, 1967, pp. 65-76

This paper presents a general discussion of the effects of sonic booms on people and structures. Only the results concerning human response will be summarized here. For a discussion of the structural effects see capsule summary SR-42.

The significant points made in this paper are the following

1. Outside exposures involve direct impingement of the sonic boom waves on the observer. Here rise time is noted to be a significant factor.

2. If the observer is inside a building, the time duration of the waves may be more important and the exposure stimuli are largely determined by the structural properties of the building. Such geometric factors as door and window configurations and framing, sheathing, and internal wall arrangement details are noted to be significant also.

HRSC-34
LOUDNESS AND PITCH SENSATIONS OF AN IMPULSIVE SOUND OF VERY SHORT DURATION
R. G. Rice and E. E. Zepler
The Journal of Sound and Vibration, Vol. 5, No. 2, 1967, pp. 285-289

In this paper theoretical evaluations of the absolute loudness and pitch sensations are investigated using the measured waveform caused by firing a pistol shot in anechoic listening conditions. The experiments described were carried out in order to see how the theoretical predictions of loudness calculated using the theory developed by Zepler and Harel (see capsule summary HR-4) work for a very short duration transient presented under free field conditions. The source used was a pistol firing 0.22 cal. blank shots in an anechoic room. The duration of the impulse was of the order of 50 µsec.

Nine subjects were asked to make loudness judgments of the pistol shots in relation to a 400 cps clickless tone burst produced by a loudspeaker. These results were then compared with calculations of the absolute loudness level of the pistol shots. These calculations were made using the following formula, which is based upon the theory of Zepler and Harel:

$$\text{Loudness level (phons)} = 102 + 10 \log (A \times 10^4)$$

Where A is numerically the area under the $k|F(\omega)|^2$ frequency curve in lb^2-sec/ft^4.

The loudness results calculated using this formula showed close agreement with the experimental findings.

The formula for loudness given in this paper is also used in a later paper by Pease (see capsule summary HRSC-35) to calculate the loudness of sonic booms.

HRSC-35
A NOTE ON THE SPECTRUM ANALYSIS OF TRANSIENTS AND THE LOUDNESS OF SONIC BANGS
C. B. Pease
The Journal of Sound and Vibration, Vol. 6, No. 3, 1967, pp. 310-314

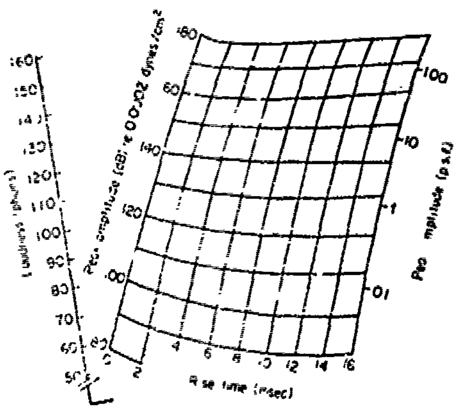
This paper discusses a computer program which was devised to obtain the Fourier transform of a complex impulsive waveform. Except where the complexity of the transient waveform itself demands it, data at closely or regularly spaced time intervals is not required by this method. The program is applied to calculations of loudness of sonic booms based on the theory of Zepler and Harel (see capsule summary HRSC-16).

This theory was originally devised and experimentally verified using ramp functions and trapezoidal pulses which could be Fourier analyzed by hand. The method was programmed for a computer in the present paper in order to enable it to be used on waveforms of more complicated shape. In determining the Fourier transform of a transient, an approximation was made in which the positions and lengths of a series of straight lines were selected to give a sufficiently close approximation to the original with the minimum possible number of lines. Thus, if the original were an ideal sonic boom N-wave, then just three lines would be used.

The Fourier transform $F(\omega)$ was computed at each of several frequencies. These frequencies were chosen to give a satisfactory coverage of the weighted energy density curve. The evaluation

of k (a w ghting factor) required an arbitrary assumption regarding a scaling factor between the amplitude parameter $|F(\omega)|$ and the power scale of the phon curves in decibels. Since this assumption required experimental justification, computation was always undertaken for several alternative values of this scaling factor. Each set of values of $k|F(\omega)|^2$ was integrated with respect to frequency by the computer and an estimated loudness obtained for each using information from Rice and Zepler (see capsule summary HRSC-34).

The figure below shows the estimated effect of intensity and rise time on loudness as determined by this method. No variation with duration was found between 50 to 200 msec. The effect of rise time on loudness can be seen to be quite significant.



Loudness of N-Wave

This paper is significant in that it put the theory of Zepler and Harel into a more easily used form.

HRSC-36
AN INVESTIGATION OF THE EFFECTS OF BANGS ON THE SUBJECTIVE REACTIONS OF A COMMUNITY
D. R. B. Webb and C. H. E. Warren
Journal of Sound and Vibration, Vol. 6, No. 3, 1967, pp. 5-385

This paper is the same as an earlier report by Webb and Warren (see capsule summary HRSC-18). The reader is referred to that capsule summary for details of this investigation.

HRSC-37
A SONIC BOOM INDEX AND HUMAN REACTION TO IMPULSIVE NOISE
Thomas H. Higgins
FAA Staff Study, April 1968

A sonic boom index is proposed in this paper for predicting human response to sonic booms. This index is based upon the concept put forth originally by Johnson and Robinson (see capsule summary HRSC-30) that the human ear will integrate the energy arising in a given band completely if the whole of the energy is received within a period short compared with the significant auditory time constant of the human ear. The index is also based upon the finding by Zepler and Harel (see capsule summary HRSC-16) that, for impulsive sound, as the rise time increases the frequency and energy content decrease and the frequency at which the maximum energy occurs also decreases.

The proposed index, which takes the above factors into account is:

$$\text{Sonic Boom Index} = \frac{K\Delta P}{t}$$

where K = arbitrarily assigned value to reduce size of the index
ΔP = overpressure in psf
t = rise time in seconds

In another paper (see capsule summary SR-43) the author shows how the same index can be used to predict structural reaction to sonic booms.

HRSC-38
CAN THE SST SONIC BOOM INDEX BE MINIMIZED THRU DESIGN?
Thomas H. Higgins
FAA Staff Study, May 23, 1968

The main concern in this paper was to determine whether or not the Sonic Boom Index could be minimized through design of the aircraft. The Sonic Boom Index is given by BI = .05 $\Delta P/t$, where ΔP is the overpressure in psf and t is the rise time in seconds. This parameter was shown by the author in previous papers (see capsule summaries HRSC-37 and SR-43) to be of use in describing human and structural response to sonic booms.

From an examination of wind tunnel test data on cone-cylinders obtained by the Boeing Company, the author concludes that a supersonic airplane having an equivalent body of revolution at the selected design Mach number which fits within a 3.5° half-angle cone cylinder would produce a signature with a finite rise time for the initial pressure change. Similar tailoring would be required to avoid a rear shock wave with zero rise time. Such a signature would give a low Sonic Boom Index.

For a more thorough discussion of the Sonic Boom Index, the reader is referred to capsule summary HRSC-37.

HRSC-39
PSYCHOLOGICAL EXPERIMENTS ON SONIC BOOMS CONDUCTED AT EDWARDS AIR FORCE BASE
K. D. Kryter, P. J. Johnson, and J. R. Young
Final Report, Stanford Research Institute, August 1968

This report is essentially the same as the one described in capsule summary HRSC-28. The reader is referred to that capsule summary for details.

HRSC-40
A PRELIMINARY STUDY OF THE AWAKENING AND STARTLE EFFECTS OF SIMULATED SONIC BOOMS
Jerome S. Lukas and Karl D. Kryter
NASA CR-1193, September 1968

This report is a description of the development of the indoor sonic boom simulator at Stanford Research Institute and the results of preliminary experiments concerned with the effects of sonic booms from this simulator on sleep and startle. Only the results of the experiments will be summarized here. For a description of the

simulation facility, see capsule summary SM-5 .

The objectives of the sleep experiments described in this report were to determine:

1. The effects of sonic booms and, comparatively, the effects of jet aircraft noise on the electroencephalographic activity and the behavioral activity of a sleeping person.

2. The extent to which individuals may adapt, according to these two measures, to sonic booms and jet aircraft noise.

3. The differences in sensitivity among individuals to awakening by sonic booms and jet aircraft noise.

A total of eight subjects participated in the investigation. Two subjects were simultaneously stimulated per night. All were 21 or 22 years of age with normal hearing.

The following preliminary conclusions were reached as a result of the sleep experiment:

1. The effects of sonic booms on the sleeping individual is, to some extent, dependent on the individual.

2. From tests of two college students it is concluded that sonic booms with intensities of 1.6 and 2.1 psf (measured outdoors) result in significantly more awakening from stage 2 sleep (which is the most prevelant sleep stage and occupies about 50 percent of the sleep cycle) than do booms with lesser intensities (.6 or .8 psf).

3. Adaptation (sleep nights 1 and 2 compared with nights 9 and 10) to booms of .6 or .8 psf during stage 2 sleep occurs and appears to result from a quantal shift in sensitivity rather than small, progressive changes in sensitivity. Adaptation to booms with intensities of 1.6 and 2.1 psf was not found during these tests.

4. Two subjects showed equal or greater awakening to the flyover noises of a subsonic jet aircraft at intensities of 103 and 113 PNdB (measured outdoors) than did the subjects exposed to sonic booms at intensities of up to 2.1 psf (measured outdoors). Possible adaptation to the subsonic jet aircraft noise could not be measured due to the small number of test sessions involved.

A startle experiment was also conducted using the sonic boom simulation room. The objectives of this study were to measure:

1. The physiological startle response to indoor sonic booms.

2. The effects of startle on the performance of a motor task.

3. The rate at which subjects adapt to indoor sonic booms as reflected by startle response and performance measures.

In this experiment twenty college students, 10 males and 10 females, with normal hearing, were divided into four experimental groups and one control group. Males and females were evenly divided among the five groups. Sonic booms of about 1.2 psf (outdoors) with 100 ms durations and 10 ms rise times were generated in the simulator for this experiment. The motor performance test was a stylus tracking board. The stylus-tracking device consisted of a square, diamond, and bullseye laid out on a board as printed circuits. In addition to performance measures the electromyographic response (EMG) of the trapezius muscle on the shoulder opposite the arm being used in the tracking task was recorded.

Each of the five experimental groups had four sessions (one day per week) of exposure to nine simulated sonic booms. Each session was approximately 45 minutes long, and consisted of nine period of three minutes each during which a boom would occur randomly at 30, 60, or 90 seconds after the beginning of the period.

The following tentative conclusions were reached as a result of the startle experiment:

1. Startle to sonic booms, as measured by an increase in skeletal muscular tension, occurs. An electromyographic response to simulated booms persisted for 36 stimulations. Although inter- and intra-session adaptation to booms was found, it did not reduce to Control Group levels in this experimental situation where the subjects anticipated the booms.

2. Sonic booms occurring coincidentally with the acquisition of skill on a new motor tracking task appear to hinder the attainment of speed but facilitate (or perhaps permit) the attainment of accuracy. In contrast, pre-practice exposure to simulated booms does not hinder the attainment of normal tracking speed but does hinder the attainment of accuracy.

This was one of the first controlled investigations of sleep and startle effects. The same simulator used in this investigation was also used in later, more extensive investigations of the startle and sleep effects of sonic booms (see capsule summaries HRSC-51 and HRSC-53).

HRSC-41
RELATIVE ANNOYANCE AND LOUDNESS JUDGMENTS OF VARIOUS SIMULATED SONIC BOOM WAVE FORMS
L. J. Shepherd and W. W. Sutherland
NASA CR-1192, September 1968

The results of a series of investigations, initiated in an effort to assess the effect of sonic boom signature modification on human subjective response, are presented in this paper. The investigation was conducted using Lockheed's sonic boom simulation facility (see capsule summary SM-6). Included in this investigation were the effects of rise time, interpeak duration, and the addition of short duration transients to the signature N-W wave.

The experiment described in this report was composed of a series of subjective comparisons designed to examine possible boom parameter-human response relationships using a paired comparison technique. In all tests the waveforms to be compared were presented to human subjects seated singly in the pressure chamber of the sonic boom simulator. Each pair of booms was presented at [illegible] second intervals, with a duration of 2 seconds between each boom of the pair. The first boom of the pair was designated the standard with the second boom being compared relative to the subjective judgment of the standard. The subject was required to state whether the second boom was louder, equal to, or softer, in the tests using loudness as a criterion, or more, equally, or less [illegible] in the case of the subjects basing their [illegible] annoyance.

The following conclusions were reached on the basis of the experiments performed:

[illegible] [illegible] of [illegible] test signatures did not [illegible] loudness or annoyance judgments.

[illegible] [illegible] test signature [illegible] and annoyance [illegible]

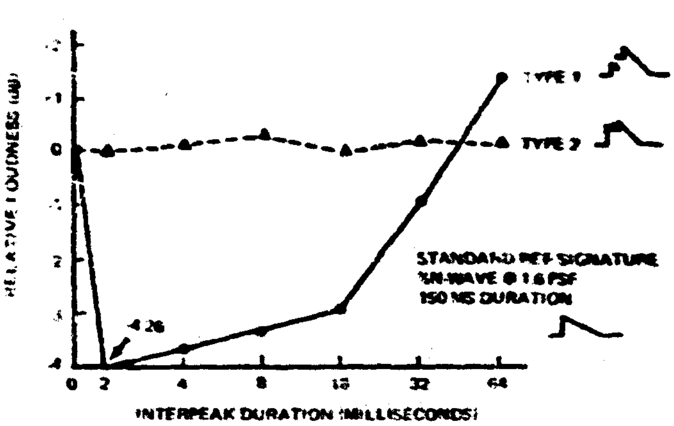
[illegible] of comparisons using [illegible] there is no difference [illegible] made with a loudness criterion and those using annoyance as a basis for comparison.

3\. [illegible] relative results for [illegible] were obtained with the standard signature set at any one of three levels, [illegible], [illegible], and [illegible] psf.

4\. The addition of a "spike" bow wave modification to an idealized 1/2 N-wave results in increased subjective loudness.

5\. As the interpeak time between adjacent successive peaks spacing of Type 1 waveforms (see figure below) is decreased from 64 msec to 2 msec, loudness decreases, as shown in the figure below, which was taken from this paper.

6\. No apparent loudness effect is noted when the interpeak spacing of Type 2 waveforms is varied (see figure below).



Relative Loudness of ½N-Waves With Different "Sawtooth" Spacing

This was an excellent investigation because it went further than any previous studies in determining the effect of various waveform parameters on human response.

HF-SC-4.
IMPLICATIONS AND JUSTIFICATION OF THE SST
B. Lundberg
Paper Presented at the Symposium on the Sonic Boom Arranged by the Netherlands Acoustical Society, Delft, October 2, 1968

In this paper four criteria for [illegible] acceptability are introduced by the author and [illegible]. These criteria are: damage to property, [illegible] to daytime hours, awakening of "average sleepers" and awakening of "light sleepers." A statistical approach is used, with many of the arguments being based on [illegible] the Oklahoma City and [illegible] boom experiments [illegible] and [illegible].

The following [illegible] are some of the [illegible] of this paper:

1\. [illegible] would be caused [illegible] over land [illegible] absolutely unacceptable.

2\. Even if it were [illegible] which would not cause any [illegible] damage [illegible] the boom, this [illegible] [illegible] boom acceptability.

3\. If the "light sleeper" criterion [illegible] acceptable [illegible] at that level which does not awaken light sleepers [illegible] with, the boom will be much [illegible] to cause any noticeable damage to property.

4\. Supersonic overland operation of the [illegible] would impose all over the world a worse than [illegible] over vast and numerous recreational and residential areas with hospitals, convalescent homes, [illegible], churches, concert halls, as well as otherwise at least partly quiet towns, [illegible], national parks and the like.

5\. For the SST boom to be acceptable (so that "light sleepers" are not awakened), its nominal intensity must be reduced to the order of 0.2 or 0.1 psf at initial cruise.

6\. An analysis of SST operation with supersonic speed limited to oversea portions of the route led to the conclusion that—apart from being grossly uneconomical and offering rather small time-saving for the passengers—such operation would be deemed unacceptable to people at sea because of the sonic boom.

In deciding what the acceptable levels of sonic boom would be, the reasoning used by the author was that the limit for the acceptable nominal boom overpressure must be set lower than the actual level of acceptability so that reasonable protection against magnified booms is ensured. Thus

the chosen level of acceptability of 0.1 to 0.2 psf was based upon an actual level of acceptability of 0.25 to 0.5 psf together with an atmospheric magnification factor of 2.5 (which it is stated would occur with a frequency of 1/1000).

In a previous paper (see capsule summary HRSC-2) Lundberg also discussed the sonic boom problem. However, the discussion of the present paper is much more extensive than that of the earlier paper.

The conclusions concerning the acceptable overpressures for light sleepers were based upon very inconclusive data obtained as a by-product of the Oklahoma City tests. Later tests by Lukas, et al (see capsule summary HR-36) showed that the lightest sleepers (men aged about 72 years) were awakened by about 32 percent of booms ranging from 0.63 to 5.0 psf in intensity. This indicates that the acceptable overpressure level of 0.1 to 0.2 psf chosen by the present author may be unnecessarily low.

HRSC-43
NOISE AND SONIC BOOM IN RELATION TO MAN
John C. Calhoun, Jr., et al
U. S. Department of the Interior Report
No. PB 180 346, November 4, 1968

This is a report to the Secretary of the Interior of a special study group on noise and sonic boom in relation to man. The study group considered various aspects of the sonic boom, together with those effects on man which would be expected from regular commercial flights of supersonic transport aircraft.

After reviewing the state of knowledge concerning all aspects of the sonic boom problem, the study group arrived at the following conclusions:

1. If commercial SST's are allowed to fly at supersonic speeds over the continental United States, the expected frequency and intensity of sonic booms would represent a significantly large increase in the noise level, and in the number of people exposed to intense noise. The response of the estimated 40 million people in the 25-mile wide swaths swept by frequent and intense booms can be expected to be similar to that of residents of neighborhoods adjacent to busy metropolitan airports under the flight paths of planes taking off.

2. Reactions to sonic booms depend on their intensity and frequency. There is considerable initial adaptation following several months of exposure, but even after several years of experiencing booms, most people find the booms objectionable or worse. Extensive research at Edwards Air Force Base, Oklahoma City, and in France, shows that, even after some years of continued exposure to sonic booms, 30% of the people exposed to booms at levels anticipated for the SST would find the booms to be "intolerable" or "unacceptable" and an additional 50% would find them "objectionable."

3. Persons experiencing sonic booms are startled and diverted or, if asleep, may be awakened in the same manner as those who hear an unexpected loud thunderclap or a large explosion. These effects may be accompanied by increased pulse rate and other minor and transient physiological changes, but they are not believed to be harmful in themselves nor to endanger hearing.

4. Studies of public reaction to aircraft and other extreme noises in the United States, France, and Britain, have consistently shown that when frequency and intensity of noise exceed certain measurable indices, many people consider the noise so objectionable that they resort to protest, to political pressures, to legal procedures and to other active (and costly) measures in efforts to achieve relief. Regular overland commercial flights of SST's over the continental United States would engender intensities and frequencies of sonic booms exceeding these indices over large areas of the country, inhabited by tens of millions of people. The negative public reaction, which can be predicted from the studies already made, would be exceedingly large.

5. Complaints and damage claims derived from sonic booms have already forced restrictions on the flights of military supersonic aircraft over populated parts of the country, although the intensities of the booms created by such aircraft are less than those predicted from the SST, and although the frequency of the booms from military aircraft has been far less than that which would occur should the SST enter into full commercial service over the continental United States. Based on this complaint history, it is estimated that regular commercial overland supersonic flight would produce from 3 to 6 million damage complaints per year to public authorities. One out of 3 to 4 complaints would be followed by a property damage claim, and about half of these claims would result in an award of damages.

6. A conservative estimate of the expected continuing annual cost of the repair of damages to houses and other structures (not counting the cost of processing claims or inspection of damages) is at least $35 million and possibly more than $80 million per year.

7. Although the value of the time saved by the busy, highly-paid persons, who would probably be the majority of SST passengers, might be 50 to 100 times greater (about $3 billion per year) than the physical damage resulting from the sonic booms, the number of people who would be gravely annoyed and disturbed probably would be larger than the number of individuals using the SST's. Subjecting this large part of the population to inescapable conditions that some regard as intolerable and many as seriously objectionable is part of the price that would have to be paid for the advantages of SST supersonic flights within the United States.

8. The only populated centers that might be kept free of the sonic booms from the SST would be the cities of the eastern megalopolis and of the Pacific Coast. This is so because all aircraft would be expected to fly at subsonic speeds within 100 to 150 miles of landing and takeoff, and flights between cities on the seaboard can be routed over the ocean. On the other hand, the intensity of the sonic booms would be considerably greater, by 3 to 10 dB, in the regions from 100 to 250 miles beyond takeoff than in the regions where the aircraft had reached its cruising speed. A large proportion of transcontinental passengers and passengers bound to and from inland cities will come from the cities of the east and west coasts. Just as with other forms of pollution, the people who obtain the benefits and the people who suffer the adverse consequences would be, in considerable part, different groups of citizens.

This paper gives a good, broad coverage of the projected problems involved in overland commercial supersonic flight.

HRSC-44
SONIC BOOMS FROM SUPERSONIC TRANSPORT
Karl D. Kryter
Science, Vol. 163, January 1969, pp. 359-367

This paper is directed to the question of the feasibility of full overland SST operation. A very broad discussion is presented of the arguments and counter-arguments concerning the severity of the sonic boom problem which would result from such overland operations. Significant results of previous sonic boom field tests and laboratory tests are summarized.

Based upon this review, it is concluded that the sonic booms from a fleet of typical SST's operating during the daytime over the United States would result in extensive social, political, and legal reactions against such flights at the beginning of, during, and after years of exposure to sonic booms from the flights. No data could be found to suggest that any other conclusion is possible.

A similar but much more extensive discussion of the problems involved in overland commercial supersonic flight is presented in the paper summarized in capsule summary HRSC-43.

HRSC-45
SONIC BOOM - RESULTS OF LABORATORY AND FIELD STUDIES
Karl D. Kryter
Proceedings of the Conference, Noise as a Public Health Hazard, Washington, D.C., June 13-14, 1968, in the American Speech and Hearing Association Reports Number 4, February 1969, pp. 208-227

This paper presents a review of the results of laboratory and field studies conducted to determine the effects of sonic booms on people. Included in the review is a brief discussion of the results of Zepler and Harel (see capsule summary HRSC-16), Shepherd and Sutherland (see capsule summary HRSC-41), Broadbent and Robinson (see capsule summary HRSC-8), and Pearsons and Kryter (see capsule summary HRSC-10). The results of several flight test experiments are also touched upon briefly.

The bulk of the paper discusses the results of the psychological experiments conducted during the Edwards Air Force Base sonic boom experiments (see capsule summary HRSC-28). The reader is referred to the capsule summary of that paper for details of those results.

HRSC-46
ACCEPTABLE NOMINAL SONIC BOOM OVERPRESSURE IN SST OPERATION
Bo Lundberg
Proceedings of the Conference, Noise as a Public Health Hazard, Washington, D.C., June 13-14, 1968 in The American Speech and Hearing Association Reports No. 4, February 1969, pp. 278-297

This is a slightly abbreviated version of an earlier paper by Lundberg (see capsule summary HRSC-42). The reader is referred to the capsule summary of that paper.

HRSC-47
SONIC BOOM - A COMMUNITY STUDY
Charles W. Nixon
Proceedings of the Conference, Noise as a Public Health Hazard, Washington, D.C., June 13-14, 1968, in The American Speech and Hearing Association Reports No. 4, February 1969, pp. 238-255

This paper summarizes the results of the Oklahoma City sonic boom tests. These results were presented in more detail in earlier papers and the reader is referred to capsule summary HRSC-14. The summary given in the present paper is very clear and concise.

HRSC-48
HUMAN RESPONSE TO SONIC BOOMS
H. E. von Gierke and C. W. Nixon
AGARD Conference Proceedings No. 42, Aircraft Engine Noise and Sonic Boom, May 1969, pp. 5-1 thru 5-15

In this report, laboratory, field, and community studies concerned primarily with human response activity which were conducted in France, the United Kingdom, and the United States are reviewed. The laboratory studies included in this review are those by Shepherd and Sutherland (see capsule summary HRSC-41), Zepler and Harel (see capsule summary HRSC-16), Pearson and Kryter (see capsule summary HRSC-10), and Lukas and Kryter (see capsule summary HRSC-40). The field studies included are Project Westminster (see capsule summary S-28), Exercise Yellowhammer (see capsule summary HRSC-19), and Exercise Crackerjack (see capsule summary HRSC-27) conducted in the United Kingdom, a public opinion survey conducted in France (see capsule summary HRSC-19), and the Oklahoma City sonic boom tests (see capsule summary HRSC-14), the St. Louis sonic boom tests (see capsule summary HRSC-13), and the Edwards Air Force Base sonic boom tests (see capsule summary HRSC-28) conducted in the United States.

The following conclusions were reached as a result of this review:

1. The probability of immediate direct physiological injury to persons exposed to sonic booms in the community is essentially zero. Long term effects on health of repeated daily exposures to sonic booms has not been investigated.

2. Startle occurs in response to the sonic boom, however, the extent to which adaptation of startle to the boom may occur is undetermined. Typical transient changes in respiration, heart rate, etc., might be expected to accompany startle.

3. Sleep interference, which may be a major determinant of public reaction, was observed for simulated sonic booms in excess of 1.0 psf for which adaptation did not occur during the test period. Long term effects of repeated daily exposure to sonic booms are not known.

4. Comparative judgments of the relative annoyance of sonic booms and aircraft noise are in good agreement and form a basis for considering the acceptability of sonic booms in terms of a Composite Noise Rating (a method of relating the undesirable aspects of noise exposure to response behavior of people by means of calculations based on the characteristics of the noise exposure).

5. A level of acceptability of sonic boom exposures in the community has not been determined.

6. Sonic booms from fully operational SST's flying of the U.S. would likely result in widespread action against the boom and its source.

7. Although physical parameters of the sonic boom signature important to annoyance or loudness have been identified, a standard procedure for measuring and describing the sonic boom is not agreed upon and in use. Peak overpressure is widely described as less than satisfactory but remains the unit and parameter found almost universally in the scientific and technical community.

This is a good summary of the state of knowledge concerning human response to sonic booms as of 1969.

HRSC-49
PERFORMING A VISUAL TASK IN THE VICINITY OF REPRODUCED SONIC BANGS
Muriel M. Woodhead
The Journal Of Sound and Vibration, Vol. 9, No. 1, 1969, pp. 121-125

The purpose of this study was to determine how quiet a sonic boom could be, yet still show measurable effects on the performance of a fast visual task performed by subjects working indoors. Recorded sonic booms were used to obtain sound pressure levels corresponding to the indoor simulation experienced for outdoor sonic booms of 0.80 psf to 2.53 psf.

A filmed display presented seventy pairs of cards, each card containing six symbols. The task was to make a comparison between the members of a pair, stating orally how many identical symbols they contained. The cards appeared in a continuous but irregular stream over a period of four minutes, so that the required rate of working was very fast, and varied with the rate of display. This activity had previously shown a temporary deterioration when accompanied by irrelevant bursts of noise.

The spectrum of the sonic boom contained mainly low frequencies in a range up to 2000 Hz. Unavoidable limitations of recording and reproduction resulted in the loss of frequencies below 30 Hz from the original boom. For test use, three sound pressure levels were prepared corresponding to booms having outdoor peak pressure of 0.80, 1.42, and 2.53 psf. The sonic boom was presented through loudspeakers in an isolated test room.

It is stated that in earlier studies the period of significant performance impairment was confined to the 30 seconds following the onset of a brief noise. In that time accurate responses fell off sharply. In the succeeding period the standard of performance rose, only to deteriorate when the next burst of noise occurred. This same pattern of impairment and fairly rapid recovery was found with the sonic booms. The quantity calculated was the difference between the number of incorrect answers in the critical post-noise half minutes and those incorrect in the quiet control periods.

It was found that after a boom of 2.53 psf the important result was an increasing tendency to omit answers. None of the effects of the booms at levels of 1.42 psf and 0.80 psf were statistically significant. It is noted, however, that the performance of 43% of the subjects who worked with 1.42 psf and 0.80 psf pressure did have a tendency to deteriorate despite the statistical insignificance.

On the other hand, out of the total sample of 108, 33 subjects actually improved after a boom, and 21 did not change in either direction. Hence, the work of exactly half of all those tested did not deteriorate because of sonic booms, especially the less noisy booms.

The significance of this investigation lies in its indication that the overpressure level at which sonic booms begin to impair performance of a fast visual task is somewhere between 1.4 psf and 2.5 psf. This agrees qualitatively with the findings of Broadbent and Robinson (see capsule summary HRSC-3), and Pearsons and Kryter (see capsule summary HRSC-10) that the maximum acceptable overpressure level is about 1.9 psf.

HRSC-50
PROCEDURE FOR CALCULATING THE LOUDNESS OF SONIC BANGS
D. B. Johnson and D. W. Robinson
Acustica, Vol. 21, No. 6, 1969, pp. 307-318

A procedure for calculating the loudness of sonic booms is described in this paper and is applied to model waveforms based on likely values of overpressure, duration, and rise time with allowance for interaction between incident and ground reflected shock waves. The determination of the energy spectrum by Fourier analysis of the waveform is described first; the way in which the standard loudness calculation for continuous sound is adapted to the case of brief transients, such as sonic booms with high levels of very low frequency energy, is then given in detail and summarized in the appendix.

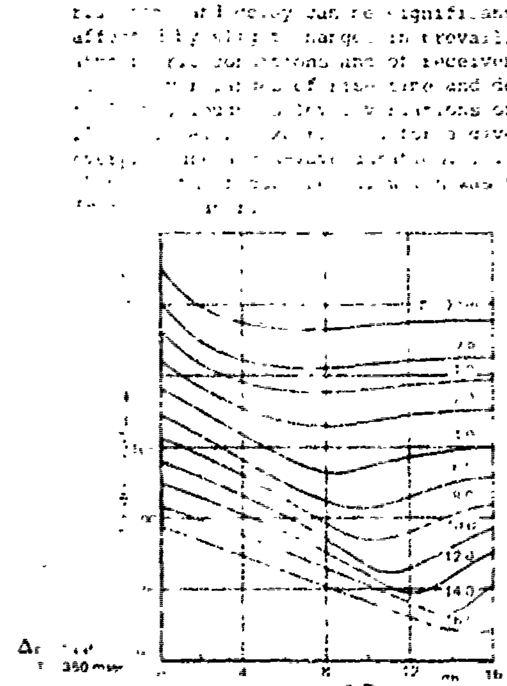
The following is a summary of the procedure and conclusion of this paper:

1. The energy spectral density of sonic booms can be determined with sufficient accuracy for loudness purposes by Fourier analysis of an approximation to the actual waveform consisting of seven straight line segments. The energy spectrum may be determined more precisely (if required) either by digital or by analogue analysis of the exact recorded waveform.

2. Assuming that for a transient sound with shorter duration than that required to evoke full aural response the latter depends on sound energy received, the equivalent band pressure levels of sonic booms may be taken as the level of continuous r.m.s. sound pressure which, over a period equal to the auditory response time, delivers an amount of sound energy equal to that of the sonic boom within the frequency band in question.

3. The [illegible] levels which occur at the low frequency end of the sonic boom energy spectrum cannot be entered directly into any [illegible] procedure for evaluating subjective [illegible] by simply extrapolating existing rules. The effect of very low frequency bands may however be taken into account by a [illegible] system based on equal loudness contours.

4. Loudness varies appreciably with changing [illegible] rise times, τ, and delay between [illegible] reflected shockwaves, δ. Both [illegible] can be significantly affected by slight changes in prevailing [illegible] and of receiver location. [illegible]



[illegible]

5. [illegible]

6. [illegible] may vary from [illegible]

7. Within the accuracy limits imposed by the slight non-parallelism of the equal loudness contours, changes in loudness level with varying overpressure (other things being constant), may be determined by a simple squared pressure ratio correction.

8. The waveform of focused sonic booms can be approximated by a sharp pressure jump followed by a relatively long exponential decay. For the same actual value of overpressure the loudness level of focused blooms is about [illegible] phons less than that of a boom of standard N-type. With an overpressure amplification factor of 4.5 such as is suggested by experimental evidence, the loudness level of focused booms of nominal ground level overpressure [illegible] psf approaches 13[illegible] phons.

The procedure used in this paper was also used [illegible] an earlier paper by Johnson and Robinson (see capsule summary HRSC-30) to evaluate the results of a flight test experiment.

This is an excellent paper. It gives a good summary of the state of knowledge as of 196[illegible] concerning loudness calculations of sonic booms.

HRSC-51
EFFECTS OF SONIC BOOMS AND SUBSONIC JET FLYOVER NOISE ON SKELETAL MUSCLE TENSION AND A PACED TRACING TASK
Jerome S. Lukas, Donald J. Peeler, and Karl D. Kryter
NASA CR-1522, February 1970.

The sonic boom simulator described in an earlier paper (see capsule summary HRSC-40) was used in the present investigation to test the effects of sonic booms and subsonic jet noise on skeletal muscle tension and a paced tracing task. In this investigation the [illegible] activity in the trapezius muscle of the shoulder in twelve subjects was monitored while they were: (1) performing a paced tracing task in the presence of occasional simulated indoor sonic booms of 2.5 psf (as measured outdoors), (2) performing a paced tracing task in the presence of occasional subsonic jet flyover noise of [illegible] PNdB, (3) performing the tracing [illegible], and (4) seated at [illegible] [illegible]

The tracing apparatus was designed [illegible] The task consisted of moving a stylus around a given track on a board at a rate set by lights [illegible] of the four corners of the board. Any time the [illegible] was ahead or behind the rate set by the lights he was instructed to lift the stylus from the board (thereby opening the circuit made when the stylus was in contact with the track) and return to position with respect to the lights. Time-on-track (TOT) was the performance measure obtained. Five sessions of at least one hour each were devoted to the training of each of the twelve subjects in the performance of the task.

The results, which were considered tentative because of the small number of subjects involved in the tests, indicated that simulated sonic booms [illegible] graphic activity in the [illegible] who performed the [illegible] as well as [illegible] In addition the [illegible] to degrade

tracing performance during the five test sessions. Flyover noises did not affect tracing performance nor result in electromyographic responses of the magnitude found as a result of the sonic booms. The control group, which performed the tracing task without booms or flyover noises, did not show any significant change in performance or change in muscle tension throughout four test sessions.

In an earlier study using the same sonic boom simulation facility, Lukas and Kryter (see capsule summary HRSC-40) used college students in an investigation which investigated the effect of sonic booms on a **self-paced tracing task**. That investigation showed that a rapid but brief increase in activity of the trapezius muscle occurred in response to simulated sonic booms. After 36 stimulations the amplitude of the electromyographic activity was reduced relative to the initial levels, but not to the level of a control group which had not been stimulated by booms.

This was a significant investigation in that it did show that booms of 2.5 psf overpressure (as measured outdoors) impaired performance of a paced tracing task. The results would have been more useful, however, if the lower limit of over pressure at which performance was impaired had been established also, such as the investigation by Woodhead (see capsule summary HRSC-49).

HRSC-52
STUDY OF THE AUDIBILITY OF IMPULSIVE SOUNDS
Sanford Fidell and Karl S. Pearsons
NASA CR-1598, May 1970

In the investigation described in this paper, six experiments were performed in an anechoic chamber to investigate the effects of various physical parameters on the perceived noisiness of impulsive signals. The parameters investigated included phase, duration, intersignal interval, repetition, and frequency. The subjects were selected from a group consisting primarily of college students ranging in age from 17 to 32 years, with a median age of twenty years. They were instructed to depress one of two lighted response switches corresponding to the more noisy of a pair of signals. Each pair of signals contained in random order an invariant standard signal and a variable comparison signal (including N-waves).

The following three major conclusions were reached as a result of this series of experiments:

1. Variations in the phase spectra of impulsive signals of similar amplitude spectra do not affect subjective judgments of perceived noisiness. Two signals of identical amplitude spectra but different phase spectra may sound dissimilar but they do not vary in judged noisiness.

2. The human ear appears to function as an energy detector in evaluating the noisiness of impulsive signals. Support for this conclusion was found in the "duration" experiment (3 dB increase in noisiness per duration doubling). There was insufficient evidence to substantiate the existence of a specific value for the ear's time constant.

3. **The common correction contours (such as Perceived Noise Level) may undercorrect in the low frequency regions and thus should be applied with caution to impulsive signals with appreciable low frequency content, such as sonic booms.**

It is important to note that the instructions for this investigation used "annoyance" and "noisiness" rather than "loudness" which was used in several other investigations (see capsule summaries HRSC-70, HRSC-50, HRSC-41, HRSC-35, and HRSC-16 for example). **It is stated that there is fairly strong evidence that judgments of "annoyance" and/or "noisiness" are somewhat different from judgments about "loudness" of impulsive sounds, and that this difference appears to be particularly important when the judgments are made of repetitive impulsive sounds.**

HRSC-53
AWAKENING EFFECTS OF SIMULATED SONIC BOOMS AND SUBSONIC AIRCRAFT NOISE ON SIX SUBJECTS, 7 TO 72 YEARS OF AGE.
Jerome S. Lukas and Karl D. Kryter
NASA CR-1599, May 1970

The same sonic boom simulation facility described in capsule summary HRSC-40 was used in the present investigation to determine the awakening effects of simulated sonic booms and subsonic aircraft noise. In this experiment six persons aged 7, 8, 41, 54, 69, and 72 years were exposed during sixteen experimental nights to simulated sonic booms (0.63 to 2.5 psf) and recorded noise (101 to 113 PNdB) from a subsonic aircraft.

The objectives of the study reported here were to determine: (1) the effects over a period of about one month, of sonic booms and subsonic turbojet aircraft engine noise on the electroencephalographic (EEG) activity and the behavioral awakening of a sleeping person, and (2) the difference in sensitivity among individuals of different age groups to sonic booms and jet aircraft noise.

The following conclusions, considered tentative because of the small number of subjects, were reached as a result of this investigation:

1. In a "typical" house, people aged about 70 years are more likely to be awakened by both simulated sonic booms and jet aircraft noise than are younger people (ages of about 8 years and 47 years).

2. People aged about 70 years are awakened by about 70 percent of the simulated sonic booms (0.63 to 1.25 psf, as measured outdoors, and on the average by about 55 percent of the subsonic jet aircraft flyovers (103-107 PNdB, as measured outdoors).

3. In a "typical" house, people aged about 7 years, 21 years, and 41-54 years are likely to be awakened about 17% of the time by subsonic jet aircraft flyovers of intensities from about 90-113 PNdB as measured outdoors, and only about 2% of the time by sonic booms of intensities 0.63 to 2.5 psf, as measured outdoors.

4. Changes in the EEG, indicating some arousal from sleep, are not as interpretable or perhaps as consistent an indicator of differences in sensitivity of the different age groups to booms or aircraft noise as is behavioral awakening.

5. Stage of sleep, as indicated by EEG pattern, is correlated with sensitivity to behavioral awakening.

6. Adaptation effects as measured by a comparison between the responses on the first six and last six nights of testing were not consistent among the groups for either booms or aircraft noise. In general, there appeared to be little adaptation to the booms but some adaptation to the aircraft noise.

7. Averaged over all age groups, it appears that booms of 0.63 to 2.5 psf are as awakening as aircraft noise of 93 to 113 PNdB (both sounds measured outdoors).

This is a very important investigation since, in establishing sonic boom acceptability criteria, it must be known which portion of the population is most likely to be awakened by sonic booms and at what level of sonic boom intensity they will be awakened. The results of this investigation gave qualitative answers to both of these questions. However, due to the small number of subjects used the results cannot be considered as conclusive.

HRSC-54
PUBLIC REACTIONS TO SONIC BOOMS
Tracor, Inc.
NASA CR-1665, September 1970

This report assesses the nature of public reaction to sonic booms in selected metropolitan areas of the United States, and identifies the major social or psychological factors that are associated with one or another type of public reaction to sonic booms of relatively modest overpressure levels. The sonic booms were generated by the supersonic SR-71 reconnaissance airplane during Air Force training and test flights. These flights were carried out in 1967 over the following six major metropolitan areas: Atlanta, Chicago, Dallas, Denver, Los Angeles, and Minneapolis.

The peak overpressures from the SR-71 flights ranged in mean values from slightly less than 1 psf to about 2 psf. The average number of booms varied from one to three booms every three days.

A total of 6,375 completed questionnaires were obtained during the periods before, during, and after the SR-71 flights. The following conclusions were reached based on the results of these questionnaires:

1. Respondents have a negative attitude toward the sonic boom, and this attitude increases rapidly in strength as the number of booms per day increases.

2. Respondents rank the boom at the top of the list of "most unwanted" sounds in the neighborhood even though they indicate their normal household activities are not disturbed any more during the SR-71 flight booming than they were before the flights. Since the majority of respondents described the booms as startling, it seems reasonable to expect that this impulse type sound would not cause disturbance of activities, but certainly it would rank high as an unwanted sound.

3. The annoyance of respondents toward the boom increased by a factor of two during booming, as compared to the level of annoyance prior to the SR-71 flights. The absolute level of annoyance, even under booming is, however, not unusually high when compared with the level of annoyance to other sounds. The pre-SR-71 flight annoyance level for booms was essentially the same as the annoyance level for "dogs and other pets"; whereas at that same time the level of annoyance for automobiles and trucks was one and one-half times that for sonic booms.

4. There are no real differences in the socio-economic level (i.e., level of occupation, income, education, etc.) of the complainants and non-complainants. The only real difference is that more than 90 percent of the complainants own their homes and feel that the boom has damaged their homes.

5. The complainants are not usually sensitive to noise in general (when compared to non-complainants).

6. Complainants choose the sonic boom as the most unnecessary and hence the first sound they would like to eliminate; whereas non-complainants rate, on the same basis, the boom slightly below hot rods/motorcycles and subsonic aircraft operations.

7. Almost three-fourths of all complainants have a strong negative attitude toward the boom compared to about one-half of the non-complainants who have the same strong negative attitude.

8. There is not a large difference in the negative attitude toward the boom between renters and non-renters; but of those who complain, over 90 percent are home owners.

9. Complainants report that their household activities are twice as disturbed compared to non-complainants.

10. There is, at best, only a slight effect of negative news media coverage upon the attitudes of the respondents toward the boom.

11. A tentative causal model relating the hearing of sonic booms to attitudes and reactions indicates that a negative attitude toward the boom must be developed before the respondent reports an increase in disturbance of his activities. It is this disturbance of activities that then relates to the level of annoyance of the respondent. The importance of this finding is that the reaction pattern appears to be different for sonic booms and subsonic aircraft noise. Although the evidence is limited, the results suggest that scientific questions may well be raised as to the meaning of "controlled" experiments equating acceptability of booms and subsonic noise.

During any one night, the intensity of the simulated booms remained constant but was changed between the three nights. The stimulus used throughout was intended to represent a reasonable facsimile of an indoor sonic boom. The sound used in this study was a recording taken from a sonic boom simulator. By altering conditions with the booth a signature of an indoor boom was obtained which closely resembled those recorded inside buildings overflown supersonically. Three intensities of this recording were used--low, medium, and high. Measurements of stimuli played through the loudspeaker in the bedroom were taken at the head position of the sleepers.

The following conclusions were reached as a result of this experiment:

1. There were more awakenings during the three "adaptation" nights (79 overall) than the subsequent four nights (69). The frequency of awakenings over the 7 nights revealed a declining trend, which may be suggestive of a gradual adaptation to the sleeping and experimental conditions regardless of stimulus intensity.

2. There were marginally fewer awakenings on control nights compared to sonic boom nights.

3. There were no great differences in the percentages of awakening in response to simulated booms of different intensities. Overall subjects awoke to 14.28% (35/245) of the sonic booms. Subjects were awakened by approximately the same number of low, medium, and high intensity sonic booms.

4. The distribution of all awakenings was found to be unequal in the first and second halves of the night; 75.53% of the awakenings occurred in the second half of the night.

5. Subjective fatigue was rated as being greater on experimental than control nights.

6. Subjects rated the quality of their sleep as worse on experimental nights than control nights, although the differences in rating were small.

7. No changes in personality factors or anxiety were evident as a result of the experiment.

8. There was a significant trend between higher neuroticism scores and more frequent awakenings in response to simulated booms.

9. The group ratings of the quality of sleep were found to be independent of experimental conditions (control and 3 experimental nights), but individuals who awoke to a higher percentage of booms tended to rate the quality of their sleep as worse.

10. It is tentatively concluded that behaviorally and subjectively, sleep interference due to sonic booms is similar to sleeping in an unfamiliar environment and strange bed.

Two previous similar investigations of the effects of sonic booms on sleep were conducted by Lukas and Kryter (see capsule summaries HRSC-40 and HRSC-53). The results of their experiments were much more quantitative in nature than those of the present investigation. Also, the simulated booms used by Lukas and Kryter were of better quality than those of the present investigation. However, the results of the present investigation are significant in that they tend to complement those of the previous investigations.

HRSC-57

AWAKENING EFFECTS OF SIMULATED SONIC BOOMS AND SUBSONIC AIRCRAFT NOISE

Jerome S. Lukas and Karl D. Kryter

Physiological Effects of Noise, Edited by Bruce L. Welch and Annemarie S. Welch, Plenum Press, New York-London, 1970, pp. 283-293

This paper is essentially the same as another paper by Lukas and Kryter described in capsule summary HRSC-53. The reader is referred to that capsule summary for details of this work.

HRSC-58

ON THE ASSESSMENT OF THE ANNOYANCE OF A SERIES OF SONIC BOOM EXPOSURES

Matchat, K., Muller, E. A., and Obermeier, F.

Acustica, Vol. 23, 1970, pp. 49-50.

This short note deals with the assessment of the annoyance of a series of sonic boom exposures, occuring during a certain period of time. The method is based upon the loudness calculation for a single boom, as given by Johnson and Robinson (see capsule summary HRSC-50).

The relation proposed for the assessment of the annoyance of a series of noise exposures, based upon EPN Levels (Effective Perceived Noise Levels) of the single noises is

$$\mathrm{EQPNL} = 10 \log_{10} \left[\frac{t_o}{T} \sum_i 10^{(\mathrm{EPNL})_i/10} \right],$$

where EQPNL = Equivalent Perceived Noise Level
EPNL = JRLL+6, where JRLL means the Johnson-Robinson Loudness Level for sonic booms
t_o = 10 seconds
and the summation is over all noise events within the time T.

Data from the Oklahoma City tests (see capsule summary HRSC-9) and the Edwards Air Force Base sonic boom experiments (see capsule summary HRSC-28) are used to show that the relation gives results that agree quite well with experimental findings.

This was the first attempt to quantitatively describe the cumulative effect on annoyance resulting from a series of sonic booms.

HRSC-59

THE AGE OF THE SUPERSONIC JET TRANSPORT: ITS ENVIRONMENTAL AND LEGAL IMPACT

John R. Montgomery

Journal of Air Law and Commerce, Vol. 36, 1970, pp. 577-614

This paper presents a discussion of the environmental and legal impact of overland commercial supersonic flight. A very general discussion of sonic boom phenomena is given, together with a

During any one night, the intensity of the simulated booms remained constant but was changed between the three nights. The stimulus used throughout was intended to represent a reasonable facsimile of an indoor sonic boom. The sound used in this study was a recording taken from a sonic boom simulator. By altering conditions with the booth a signature of an indoor boom was obtained which closely resembled those recorded inside buildings overflown supersonically. Three intensities of this recording were used--low, medium, and high. Measurements of stimuli played through the loudspeaker in the bedroom were taken at the head position of the sleepers.

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The loudness calculation procedure developed by Zepler and Harel (see capsule summary HRSC-16) is reviewed briefly. Also touched upon in the review is the work of Pease (see capsule summary HRSC-35), Woodhead (see capsule summary HRSC-49, Webb and Warren (see capsule summary HRSC-18), and several others.

This is a very brief review and the aforementioned studies are not discussed in any depth.

HRSC-64
LEGAL ASPECTS OF MILITARY SONIC BOOMS
William F. McCormack
Proceedings of the Society of Automotive Engineers, February 8, 1971, pp. 205-217

The purpose of this paper is to show some of the legal developments which have resulted from military supersonic flight. The discussion includes: (1) a brief description of sonic boom phenomena; (2) administrative remedies; (3) remedies under the Federal Tort Claims Act; (4) liability for nuisance; (5) a discussion of cases involving the Tucker Act; and (6) remedies in state courts. The discussion in each of these areas is quite extensive, making this an excellent paper.

HRSC-65
EFFECTS OF AIRCRAFT NOISE ON HUMAN SLEEP
Jerome S. Lukas
Paper Presented at American Industrial Hygiene Conference, Toronto, Canada, May 24-28, 1971

A review is presented in this paper of the studies performed by the Stanford Research Institute concerning the effects of aircraft noise and sonic booms on sleep. The reader is referred to capsule summaries HRSC-40 and HRSC-53 for a description of these studies.

After reviewing the SRI studies the following conclusions are made:

1. The sleep of children tends to be uniformly unaffected by simulated sonic booms or subsonic jet aircraft noise over a wide range of intensities.

2. Men aged about 50 years, on the average, were awakened by about 18 percent of the simulated sonic booms ranging from 0.65 to 5.0 psf in intensity, and awakened to an equal extent by subsonic jet flyover noises ranging in intensity from 101 to 119 PNdB.

3. On the average, old men of some 70 years of age were awakened by about 28 percent of the sonic booms of 0.65 to 5.0 psf intensity, and to an apparently slightly greater (about 4%), but statistically insignficant, degree by subsonic jet flyover noises ranging in intensity from 101 to 119 PNdB.

4. For middle-aged and old men, sonic booms of 2.0 psf are, on the average, as awakening as subsonic jet flyover noices of about 110 PNdB. An increase or decrease of about 6 PNdB of the jet flyover noises has the same effect on behavioral awakening as a doubling or halving of the sonic boom intensity.

The studies conducted by Lukas and Kryter at SRI form the main basis for what is known concerning the effects of sonic booms on sleep. This paper gives a good, brief summary of the results of these studies.

HRSC-66
A STUDY OF SENSITIVITY TO NOISE
R. W. Becker, F. Poza, K. D. Kryter
Federal Aviation Administration Report No. EQ-71-4, June 1971

In the study described in this paper, 140 subjects were exposed to simulated sonic booms and recorded residential noises in one, two, or three two-hour sessions over a period of six months. The sonic boom simulation facility used here is the same one described in capsule summary HRSC-40. The other noises consisted of those due to a subsonic jet, a vacuum cleaner, a barking dog, a motorcycle, truck traffic, and freeway traffic. The subjects were asked to rate how annoying they found each of the noises. Electrophysiological measures of heart rate and electromyographic responses to the stimuli were analyzed. Biographical, demographical, and personality inventories for each of the subjects were also obtained.

The following conclusions were reached as a result of this investigation:

1. The relative ranking of the perceived annoyance of the various noises remained constant over the six-month duration of the experiment. A 2.5 psf boom was distinctly the most annoying sound. A 1.25 psf boom was rated more annoying than all other noises except the 90-dBA jet flyover and the 81 dBA vacuum cleaner. A 0.63 psf boom was rated less annoying than all noises except for the 67-dBA truck and the 62-dBA motorcycle recording. (These sonic boom levels are what would be measured outdoors. The subjects actually heard the booms indoors.)

2. Personality-type tests do not appear to provide sufficient additional information related to sensitivity to noise to justify the time required for their completion.

3. Analysis of the physiological reactions to the noise indicated a definite heart rate acceleration in response to the simulated sonic booms. This was true even of the 0.63 psf boom which was not rated as very annoying.

This was the first extensive investigation of the relative annoyance of sonic booms and common residential noises. Many previous investigations (see capsule summary HRSC-53, for example) had dealt with the relative annoyance of sonic booms and subsonic aircraft noise, but none of these included any other annoying residential sounds.

HRSC-67
EFFECTS ON MUSCLE TENSION AND TRACKING TASK PERFORMANCE OF SIMULATED SONIC BOOMS WITH LOW AND HIGH INTENSITY VIBRATIONAL COMPONENTS
Jerome S. Lukas, Mary E. Dobbs, and Donald J. Peeler
NASA CR-1751, June 1971

The purpose of the experiment described in this report was to determine the relative contribution of the vibrational component generated in a room from simulated sonic booms on the electromyographic and performance responses of human subjects. In order to accomplish this, four subjects were assigned randomly to each of the following groups: (1) paced tracing task, with booms and with relatively low intensity vibration (subject's chair and tracing table on a vibration-isolation platform); (2) paced tracing task, with booms and with relatively high intensity vibration (subject's chair and tracing table on floor); (3) reading of light material with booms, and with low intensity vibration; and (4) paced tracing task only.

The sonic boom simulator described in an earlier paper (see capsule summary HRSC-49) was used again in the present investigation to generate simulated sonic booms having durations of about 300 ms, intensities of about 2.5 psf, and effective rise times of about 10 ms, as measured outdoors.

The subjects were 16 tool and die makers and machinists between 40 and 62 years of age, with a mean age of 50 years. The tracing task performed in this experiment was the same as that described in capsule summary HRSC-51, which consisted of moving a stylus around a rectangular track at a pace determined by lights on the board.

Three response measures were obtained: (1) Time-on-Track (TOT); (2) Electromyographic Activity Level (EMG), which was obtained from the trapezius muscle (located in the shoulder) contralateral to the arm being used in the tracing task, and (3) errors were calculated as the number of times the subject was off the assigned track.

The following conclusion was reached as a result of this experiment: Among machinists and tool and die makers, who normally work in noisy environments, the periodic occurrence of the noise and vibration associated with simulated sonic booms, of an outdoor intensity of 2.5 psf, had no statistically significant effect on performance of a tracing task requiring a fair degree of perceptual-motor coordination, or on skeletal muscle tension.

The significance of this investigation is that it demonstrated that the performance impairment found in a previous investigation (see capsule summary HRSC-51) due to sonic boom exposure was not due simply to the effects of the room vibrations on the subjects but was due rather to the startle effect.

HRSC-68
DISTURBANCE OF HUMAN SLEEP BY SUBSONIC JET AIRCRAFT NOISE AND SIMULATED SONIC BOOMS
Jerome S. Lukas, Mary E. Dobbs, and Karl D. Kryter
NASA CR-1780, July 1971

The same sonic boom simulation facility described in capsule summary HRSC-40 was used in the present experiment to investigate the disturbance of human sleep by subsonic jet aircraft noise and simulated sonic booms. Two previous experimental studies of the effects of booms and subsonic jet aircraft noise on sleep were conducted with the aid of this simulator. In the first (see capsule summary HRSC-40), a pilot study, six college students were subjects; in the second (see capsule summary HRSC-53), six subjects ranging in age from 7 to 22 years were tested.

The results of the second study were considered tentative because only two subjects were in each of three age groups (young--about 7 years of age, middle-age--about 51 years, and old--about 71 years of age). Consequently, the study reported in the present paper used four additional subjects in each of the three age groups in order to explore further the effects of sonic booms and subsonic aircraft noise on sleep in persons of different ages.

The subjects were exposed for 20 nights to simulated sonic booms and subsonic jet flyover noises. Four intensities of each stimulus were usually presented twice each night.

The following conclusions were reached as a result of this study:

1. The sleep of children (5 to 8 years of age) tends to be essentially unaffected by either simulated sonic booms or subsonic jet flyover noise over a wide range of intensities (from 0.63 to 5.0 psf for sonic booms, as measured outdoors, and 101 to 119 PNdB for flyover noise, as measured outdoors).

2. On the average, middle-aged men, about 50 years of age, in a "typical" house are awakened by about 18 percent of the simulated sonic booms ranging in intensity from 0.63 to 5.0 psf, and to an equal extent by subsonic jet flyover noises ranging in intensity from 101 to 119 PNdB.

3. On the average, old men, about 72 years of age, in a "typical" house are awakened by about 32 percent of booms ranging from 0.63 to 5.0 psf in intensity, and to about the same extent by subsonic jet flyover noises of 101 to 119 PNdB.

4. Within both the middle-aged and the old groups there appear to be at least two identifiable subgroups of different sensitivity to noise during sleep. For the middle-aged group the so-called high sensitivity subgroup is about ten times more likely to be awakened by simulated booms or flyover noise than is the subgroup of low sensitivity. In contrast, the old subgroup of high sensitivity is only about twice as likely to be awakened by the stimuli as is the old subgroup of low sensitivity.

5. On the average, for middle-aged and old groups, sonic booms of 2.0 psf are as awakening as subsonic jet flyover noises of about 110 PNdB (both sounds as if measured outdoors). It is pointed out by the authors that these data are in agreement with those of Kryter, et al. (see capsule summary HRSC-28) and Broadbent and Robinson (see capsule summary HRSC-8) with respect to the awake subject, and

to those reported earlier for the sleeping human (see capsule summary HRSC-53). In addition, for any increase or decrease of about 6 PNdB in flyover noise the change in rate of awakening is approximately the same as doubling or halving the intensity of the sonic boom.

This investigation did not result in any significant conclusions that had not already been reached in the earlier investigations. However, it did serve to substantiate the previous findings.

HRSC-69
IS CIVIL SUPERSONIC AVIATION JUSTIFIED?
Bo Lundberg
Paper Presented to the Committee on Social and Health Questions of the Council of Europe at its Meeting in Stockholm on July 6, 1971, N71-33438-441

This paper presents a review of the pros and cons of commercial supersonic aviation. Only the portion of the report dealing with the sonic boom problem will be summarized here.

The sonic boom discussion begins with a brief review of sonic boom phenomena. The various characteristics of sonic boom pressure signatures are defined and magnifications due to atmospheric effects and aircraft maneuvers are discussed. It is then stated that it is the opinion of the author that most of the extensive tests that were conducted during the 60's to determine the effects of sonic booms on structures were an unnecessary waste. The reasoning is that the most critical sonic boom acceptability criterion is the "light sleeper" criterion, which sets the acceptable boom level as the highest overpressure which does not awaken a light sleeper. Since this overpressure level is much lower than the level at which structural damage results, the establishment of this acceptability level should have taken precedence over the structural response testing.

It is then emphasized that extensive flight test investigations concerning the effects of sonic booms on all types of boats, ships, and maritime wildlife must be conducted before commercial supersonic flights over sea are allowed.

This paper is very similar to an earlier paper by Lundberg (see capsule summary HRSC-42).

HRSC-70
THE LOUDNESS OF SONIC BOOMS HEARD OUTDOORS AS SIMPLE FUNCTIONS OF OVERPRESSURE AND RISE TIME
D. N. May
Journal of Sound & Vibration, Vol. 18, No. 1, September 8, 1971, pp. 31-43

In this paper semi-empirical formulae are presented which can be used to calculate the loudness of sonic booms heard outdoors as functions of their peak overpressures and rise times only. These formulae were based upon the more complex loudness calculations of Zepler and Harel (see capsule summaries HRSC-16 and HRSC-35) and Johnson and Robinson (see capsule summaries HRSC-30 and HRSC-50). Five different relations between loudness, L, maximum overpressure, ΔP, and rise time, Δt (defined as time from wave onset to point of maximum pressure) are given. The following relation is the most simple, yet it gives results nearly as good as the other four:

$$L = (\Delta P)_{dB} - \Delta(t) - 12$$

where L is in phons and Δt is in msec.

An experimental assessment of the five relations was made using 34 sonic booms caused by flights of F-104G Starfighter aircraft over Meppen, West Germany and up to 14 subjects. The flight path of these aircraft lay directly over the subjects. The scheduling of the booms was not known in advance of the experiment, nor was the availability of the subjects. Consequently a "psychophysical" procedure was used in which subjects could participate, without disruption to their normal duties and without the use of comparison sounds, by filling in a short questionnaire as and when they heard a boom. The subjects were instructed to assess the loudness of the bangs by comparing them to the sound of a fairly near clap of thunder, which was assigned a value of 10.

The results of this experiment showed that the semi-empirical relations correlated with judged loudness at least as well as did the more complex ones. It is concluded that the semi-empirical formulae, by virtue of their simplicity, are of much more use in loudness calculations than the more complicated formulae.

The formula given for calculating the loudness of sonic booms is very simple to use in contrast to previous methods. This makes possible rapid determination of the relative merits of two different sonic boom pressure signatures. However, further experimental verification is necessary to define the accuracy and limits of the formula.

HRSC-71
EFFECTS OF SIMULATED SONIC BOOMS ON TRACKING PERFORMANCE AND AUTONOMIC RESPONSE
Richard I. Thackray, R. Mark Touchstone, and Karen N. Jones
Aerospace Medicine, Vol. 43, No. 1, January 1972, pp. 13-21

The study discussed in this paper was conducted in order to provide further information on the effects of sonic booms on psychomotor performance and autonomic activity, including recovery patterns following stimulation and the effects of boom repetition. Stimuli were produced by an indoor sonic boom simulator with overpressure levels of 1.0, 2.0, and 4.0 psf (as measured "outdoors") and durations of 295 milliseconds. Because of design characteristics of the simulator, rise times of the simulated sonic booms increased in a manner which was almost proportional to increases in overpressure. Thus, rise times of the simulated booms employed ranged from approximately 7 msecs for a 1 psf boom to 21 msecs for a 4 psf boom.

The simulator was an indoor sonic boom simulator designed by Stanford Research Institute and similar to one used by Lukas and Kryter (see capsule summary HRSC-40). The test room was 13-1/2 x 12 x 8 feet, one wall of which formed one of the sides of a hermetically sealed pressure

chamber. Booms were produced by a motor-actuated piston which generated an N-wave of pressure in the chamber. Overpressure was changed by varying piston travel and duration by changing motor speed. There were two windows in the test chamber, one of which was used for one-way observation.

The subjects were forty paid male college students between the ages of 18 and 25. They were assigned to one of three experimental groups or the control group on a simple rotational basis.

The tracking task was to attempt to keep a randomly moving spot at the center of an oscilloscope by means of a small control stick located at the right hand of the subject. The effects of the booms on both autonomic activity and performance were evaluated in terms of change from pre-stimulus levels.

The results showed no evidence of performance impairment for any of the overpressure levels. Rather, performance improved significantly following boom stimulation along with heart-rate deceleration and skin conductance increase. It is concluded that the obtained pattern suggests that the simulated booms may have elicited more of an orienting or alerting response than a startle reflex. It is pointed out, however, that since faster rise times of the simulated booms might have increased loudness sufficiently to change these results considerably, care should be taken to avoid drawing unwarranted conclusions, relative to general sonic boom effects, on the basis of these findings alone.

A previous investigation by Lukas, Peeler, and Kryter (see capsule summary HRSC-51) showed that exposure to sonic booms did result in impaired performance of a paced tracking task. It was also found by Woodhead (see capsule summary HRSC-49) that performance of a visual task was impaired by exposure to booms of 2.5 psf. The contrast between these results and those of the present investigation may be due merely to the difference in the task being performed in each case.

HRSC-72
HUMAN RESPONSE TO SONIC BOOM IN THE LABORATORY AND THE COMMUNITY
H. E. von Gierke and C. W. Nixon
Sonic Boom Symposium, The Journal of the Acoustical Society of America, Vol. 51, No. 2 (Part 3), February 1972, pp. 766-782

This paper is exactly the same as the one discussed in capsule summary HRSC-48. The reader is referred to that capsule summary for details of this work.

HRSC-73
EXPERIMENTS ON THE EFFECT OF SONIC-BOOM EXPOSURE ON HUMANS
Ragnar Rylander, Stefan Sorensen, Kenneth Berglund, and Carina Brodin
Sonic Boom Symposium, The Journal of the Acoustical Society of America, Vol. 51, No. 2 (Part 3), February 1972, pp. 790-798

In the experiments described in this paper the effects of sonic-boom exposure on the reactions of humans were studied in a field exposure experiment. In addition to the experiments on humans, studies were also performed on the response of reindeer, but for a discussion of these studies the reader is referred to capsule summary AR-13.

Forty-two sonic booms with levels varying from about 0.2 to 10.5 psf were generated by Swedish military aircraft flying over a research camp in northern Sweden. The exposure effects were evaluated using a performance and a tracking test at boom pressures up to 1.2 psf.

In the performance test, subjects watched a film where equality in a number of symbols between stationary and moving cards on a film screen was to be indicated. In the tracking test a pointer connected to a steering wheel was to be kept on an irregularly moving tape on a rotating belt. The subjective reactions of test persons and military recruits under the sonic-boom carpet were studied by means of a questionnaire.

The following results were obtained as a result of these experiments:

1. In the performance test, the sonic boom exposure caused a significant interruption in answer reporting during the 5 to 14 seconds immediately after exposure.

2. In the tracking test, the duration of deviations from the tape was found to increase immediately after boom exposure.

3. An overpressure-response relationship was found for the exposure effect on the performance test, but was not demonstrated on the tracking test. The relationship for the performance test showed a general increase in the percentage of persons annoyed by the booms as overpressure increased.

4. There was a lower proportion of annoyed and very annoyed reported by the test subjects as compared with the soldiers. This was felt to be due to the very positive attitudes of the test subjects towards the experiment as a whole, as revealed by the questionnaires.

A different type of tracking task was used by Lukas, Peeler, and Kryter (see capsule summary HRSC-51) to test the effect of laboratory sonic booms. In that experiment it was found that exposure to outdoor boom pressures of about 2.5 psf caused an increase in skeletal muscle tension and a decrease in the accuracy of tracking. In the present results, significant decreases in the tracking index were sometimes found at indoor boom pressures of about 0.2 psf.

Woodhead (see capsule summary HRSC-49) used the same performance test used here and found the same pattern of response. That study showed that outdoor boom pressures of 2.53 psf resulted in a significant decrease in the number of correct answers during a 30 second period after the exposure. The indoor pressure was not reported.

HRSC-74
SONIC BOOM EXPOSURE EFFECTS I.3: GENERAL CONSIDERATIONS ON SONIC BOOM RESEARCH
Jacques Balazard
Journal of Sound and Vibration, Vol. 20, February 22, 1972, pp. 499-503

This paper discusses a proposed research scheme to investigate the effects of sonic booms on humans, animals, structures, and other objects. The basic research scheme is divided into three separate aspects: (1) effect of a few booms on a few objects; (2) effect of a multitude of booms on a few objects; and (3) the effect of a multitude of booms on a multitude of objects. The types of sonic boom generators or simulators and the type of equipment, etc. necessary to carry out each of the three investigations is discussed briefly.

HRSC-75
SONIC BOOM EXPOSURE EFFECTS II.4: ANNOYANCE REACTIONS
P. N. Borsky
Journal of Sound and Vibration, Vol. 20, February 22, 1972, pp. 527-530

This paper presents a summary of the results of the significant field experiments that have been conducted to investigate the annoyance response of communities to sonic booms. Included in the review are the St. Louis, Oklahoma City, and Edwards Air Force Base studies (see capsule summaries HRSC-15, HRSC-14 and HRSC-28, respectively) conducted in the United States, and the unpublished (at the time this paper was written) results of studies conducted in France, Great Britain, and Sweden.

In the French study, which had not been completed at the time this paper was written, 3900 people were interviewed concerning their response to over 100 supersonic overflights, including 30 Concorde flights. In the British study 3000 people were interviewed concerning their response to Concorde test flights. The Swedish study involved the exposure of 200 soldiers to 42 sonic booms.

The following are some of the conclusions reached as a result of this review:

1. Both French and American experience indicates that most people can consistently recognize sonic booms after a brief learning period.

2. Vibration and rattling of homes and furnishings are the most frequently reported causes of annoyance.

3. Information on interference with sleep is quite limited, but it is believed to be an important effect which usually produces intense annoyance.

4. Interference with communication was reported by relatively few people in the French and American studies.

5. Belief has also been widespread that sonic booms cause property damage. This probably contributes to annoyance reactions. About 45% of the Oklahomans believed booms caused such damage, and 65% of the British and 60% of the French respondents had similar beliefs.

6. Although different measures of annoyance were used in the various studies, making precise comparison difficult, it was found that about half of all persons exposed to booms report more than a little annoyance. In the Oklahoma City Study, 56% of the respondents reported serious annoyance after 6 months exposure to sonic booms. In the French study, slightly less than 50% reported similar annoyance responses. In Sweden, 50 to 60% of the respondents reported annoyance. In the British study, about one-third of those who heard the booms reported annoyance.

7. Very few definitive findings can be stated about the relationships that annoyance has to the number of exposure over time, the adaptation process, or the sonic boom overpressures.

8. No evidence was found that annoyance to sonic booms decreases over a period of time.

This is a good brief review of the results of of community response studies that have been conducted in Europe and the United States.

HRSC-76
SONIC BOOM EXPOSURE EFFECTS II.2: SLEEP EFFECTS
C. G. Rice
Journal of Sound and Vibration, Vol. 20, February 22, 1972, pp. 511-517

This report presents a brief, general review of the quantitative data which express sleep interference in terms of certain aspects of sleep patterns (sleep stage and accumulated sleep time), individual differences (age, sex, temperament, responsiveness), and stimulus variables (type of sound and intensity). The effects of such interference on health, performance, and attitudes are also briefly commented upon. The relationship between the findings of laboratory studies and the real-life situation is discussed. Also, some suggestions are given for standardization of some of the experimental approaches used in different laboratories.

The following are some of the main points brought out in this review:

1. Awakening in response to a stimulus appears more likely to occur as sleep time is accumulated, regardless of sleep stages.

2. Older people are more easily awakened by sonic booms and ordinary noise.

3. The evidence of both field and laboratory studies on sonic boom and aircraft noise suggests that women are more easily awakened than men.

4. Experimental data suggest that adaptation to the laboratory environment is still taking place after several consecutive nights of sonic boom exposure. This indicates that sleep experiments should be

conducted over periods of at least two to three weeks.

5. Existing information indicates that the attitudinal and behavioral reaction of a community to noise can be predicted with reasonable accuracy only by combining the annoyance due to the noise in question with the total human reactions to other noises in the environment. There is no reason to assume that the sonic boom should be treated any differently.

This is a good, brief general review of the state of knowledge as of 1971 concerning the effects of sonic booms on sleep. A similar, but more quantitative and extensive review of the state of knowledge as of 1970 was given by Morgan (see capsule summary HRSC-55).

HRSC-77

SONIC BOOM EXPOSURE EFFECTS II.3: STARTLE RESPONSES

R. I. Thackray

Journal of Sound and Vibration, Vol. 20, February 22, 1972, pp. 519-526

A brief review of the startle effects of sonic booms on people is given in this paper. It is stressed that it is particularly important to distinguish between the "startle" resulting from sonic booms and a surprise or orienting response, since the effects on performance of these types of responses could be quite different. The startle reflex is stated to be primarily a muscular response where the complete reaction consists of a series of involuntary contractions beginning at the head with the eye blink and rapidly progressing to the legs. The most characteristic feature of the orienting response is a turning of the body or head towards the source of the stimulus, to facilitate sensory intake. The involuntary muscular response of the startle reflex, being basically disruptive, tends to impair ongoing performance, while the orienting response serves to alert the organism.

The following are some of the main points brought out in the review of the "startle" and "orienting" response of people to sonic booms and other impulsive noises:

1. There is almost complete agreement among studies employing short bursts of high-intensity stimuli, that performance immediately following such stimuli is temporarily impaired. Tasks involving complex perceptual and/or cognitive processes may be impaired for longer periods than tasks requiring precise arm-hand coordination. Although the major impairment is at a maximum immediately following stimulation, significant impairment may persist for up to 30 seconds.

2. Studies employing real or simulated sonic booms have found results which range from performance impairment, to generally non-significant effects, to performance improvement. Thus, it is not possible to draw any general conclusions concerning the effects of real or simulated sonic booms on performance. All that can be said is that impulsive acoustic stimuli less than some "threshold value" may either have no effect on performance or increase it (possibly accompanied by orienting reactions) while levels of impulsive acoustic stimulation greater than the "threshold value" may temporarily impair performance, possibly as a result of startle reflexes.

3. Although objective indices of startle are preferable in the present state of knowledge, subjective indices could be useful if it is demonstrated that they correlate with the objective ones.

4. All evidence indicates that the startle reflex does not completely habituate with repeated presentation of the stimulus.

5. It is reasonably well established that both the physiological and behavioral aspects of the orienting response will habituate completely with repeated stimulation--possibly after 10-30 repetitions. However, even a minor change in the characteristics of the stimulus may result in a partial on complete reappearance of the response.

6. Earlier studies agree, essentially, that subjects with the greatest skill levels prior to presentation of the stimulus display the least impairment.

This is a good, general, non-quantitative summary of the state of knowledge as of 1971 concerning the startle effects of sonic booms.

HRSC-78

RESIDUAL PERFORMANCE EFFECTS OF SIMULATED SONIC BOOMS INTRODUCED DURING SLEEP

W. Dean Chiles and Georgetta West

Federal Aviation Administration, Report No. FAA-AM-72-19, May 1972

This paper discusses the results of an investigation conducted to determine the residual performance effects of simulated sonic booms introduced during sleep. This study was part of a larger study which included the investigation described in capsule summary HRSC-80.

There were eight paid subjects in each of the following three age groups: young adults (21 to 26 years old), middle-aged (40 to 45 years old), and elderly (60 to 72 years old). Two subjects at a time spent 21 consecutive nights in a sleeping room equipped for sonic boom simulation and electrophysiological monitoring. Both subjects in each pair were from the same age group.

For the first five nights the subjects were permitted to adapt to the sleeping quarter, and no booms were presented. On nights 6 through 17, the subjects were exposed to hourly sonic booms starting at 2300 hours and continuing until 0600 hours the following morning. Each boom had an intensity of .1 psf measured inside the sleeping room and 1 psf measured in the pressure chamber adjacent to the sleeping room. The rise time of the boom, as recorded in the sleeping quarters was 12 msec, and it had a duration of approximately 280 msecs. The last four nights of the sequence were designated recovery sessions.

Each morning and each evening the subjects completed "The Multiple Task Performance Battery." The apparatus presented two passive and two active tasks. The passive tasks consisted of monitoring warning lights and probability meters; the active tasks consisted of mental arithmetic and pattern discrimination.

The results provided no evidence that exposure to simulated sonic booms during sleep produced measurable consequences with respect to complex performance.

This is a significant investigation since it is the only one that has ever been conducted on this topic.

HRSC-79
THE SONIC BOOM-WEIGHING ITS IMPLICATIONS FOR POLICY CONSIDERATIONS
P. L. Eggleton
Canadian Aeronautics and Space Journal, May 1972, pp. 117-122

This paper presents a very general discussion of the various sonic boom factors which may be of concern to a particular country and explores possible policy alternatives based on them. Three policy alternatives are suggested that a country could invoke: (1) the complete barring of overland supersonic flight; (2) the adoption of the concept to permit overland supersonic flight along segments of strictly-controlled corridors; and (3) no restrictions on overland supersonic flight. A discussion of the implications of supersonic overland flight is then given.

HRSC-80
SONIC BOOMS AND SLEEP: AFFECT CHANGE AS A FUNCTION OF AGE
Roger C. Smith and Gary L. Hutto
Federal Aviation Administration, Report No. FAA-AM-72-24, June 1972

This study concerned the measurement of mood changes resulting from simulated sonic booms occurring during sleep. The Composite Mood Adjective Checklist (CMACL), a measure of mood states, was employed as the index of such distress. It is an 80-item inventory which provides an overall index of degree of positive affect, as well as scores for 15 individual mood factors such as anxiety, agression, friendliness, and so on. It was the purpose of this study to determine to what extent CMACL scores are influenced by exposure to simulated sonic booms during sleep, and to measure this effect in terms of the age group, i.e., young-adult, middle-aged, or elderly, to which an individual belongs. A second purpose was to determine to what extent the effects of repeated sonic boom exposure during sleep are cumulative with respect to affective states.

There were eight paid subjects in each of the following three age groups: young-adults (21 to 26 years old), middle-aged (40 to 45 years old), and elderly (60 to 72 years old). Two subjects at a time spent 21 consecutive nights in a sleeping room equipped for sonic-boom simulation and electrophysiological monitoring. Both subjects in each pair were from the same age group. For the first five nights the subjects were permitted to adapt to the sleeping quarters, and no booms were presented. On nights 6 through 17, the subjects were exposed to hourly sonic booms starting at 2300 hours and continuing until 0600 hours the following morning. Each boom had an intensity of .1 psf measured inside the sleeping room and 1 psf measured in the pressure chamber adjacent to the sleeping room. The rise time of the boom, as recorded in the sleeping quarters was 12 msec, and it had a duration of approximately 284 msecs. The last four nights of the sequence were designated recovery sessions. The subjects completed the composite mood adjective checklist in the evening before retiring and in the morning after waking on each of the 21 days.

The results showed that substantial effects relating to the age of subjects, irrespective of boom presentations, were obtained. However, no change in moods attributable to the occurrence of simulated sonic booms was found. It was concluded that simulated sonic booms of such low intensity were unlikely to have adverse consequences on the mood states of most individuals.

This was the first investigation of the effect on mood states of exposure to sonic booms during sleep.

HRSC-81
INITIAL CALIBRATION AND PHYSIOLOGICAL RESPONSE DATA FOR THE TRAVELING-WAVE SONIC-BOOM SIMULATOR
Richard Carothers
Institute for Aerospace Studies, University of Toronto, UTIAS Technical Note No. 180, August 1972

This report deals with the initial calibration of a sonic boom simulation facility which was designed and built at the University of Toronto Institute for Aerospace Studies. Also presented are the results of tests showing the effects of sonic booms on human heart rate and hearing. Only the latter portion of the report is summarized here. For a description of the simulation facility, see capsule summary SM-16.

The first set of tests was carried out before the installation of the fiberglass acoustical filtering section. Thus the sonic booms had a superimposed broadband jet noise which increased their subjective loudness. In these tests 20 subjects were exposed to 50 sonic booms at the rate of 25 per minute. The "noisy" booms had an overpressure of 2 psf, a duration of 80 msec and a rise time of 3 msec. Records were made of the initial (immediately before boom exposure) and increased (immediately after boom exposure) heart rates as well as the time taken for the increased heart rate to return to its pre-stimulus level. Audiograms were completed before and about 2 minutes after the 50 sonic-boom exposures.

After the installation of the fiberglass acoustical filtering section, a more detailed study, using the "reduced noise" sonic booms of 2, 4, and 8 psf overpressures, 80 msec duration and 3 msec rise times, was then made of hearing and heart rate responses. Audiograms were again performed before and about two minutes after exposure to so sonic booms. The heart rate measurements, however, were somewhat modified. Each subject was in a reclining position and

was allowed to rest for a short time. Before any sonic boom exposure, each subject had to answer a simple question, perform a simple task, and solve a simple mathematical problem. Because the second set of sonic boom measurements required more time to perform, it was necessary to limit the experimental group to 8 subjects.

The results indicated that sonic booms of up to 8 psf peak overpressure do not have a detrimental effect on human hearing or heart rate. However, the subjective evaluation of the sonic booms indicated that peak overpressures of 4 psf or more would be unacceptable to most people.

The significance of this investigation lies in its fairly conclusive finding that exposure to very frequent, strong sonic booms does not affect human hearing.

HRSC-82
SIMULATED INDOOR SONIC BOOMS JUDGED RELATIVE TO NOISE FROM SUBSONIC AIRCRAFT
Karl D. Kryter and Jerome S. Lukas
NASA CR-2106, August 1972

The sonic boom simulation facility described in capsule summary HRSC-40 was used in the present investigation to obtain subjective comparisons of sonic booms and noise from subsonic aircraft. Twenty subjects ranging in age from 25 to 49 years (average age of 34.8 years) participated in the experiment.

The subjects, randomly divided into six groups, were each tested for three or four consecutive days, during sessions of approximately one and one-half hour duration. In each session each subject was required to make sixteen paired comparisons between a simlulated sonic boom with certain characteristics and a recorded subsonic fanjet flyover noise.

The following conclusions were reached as a result of this investigation:

1. Spectral differences due to variations in the rise times of sonic booms affect the judged noisiness of the booms as heard indoors. A boom having a rise time of 3.5 msec and a peak overpressure of 1.5 psf (as measured outdoors) was judged relative to the aircraft noise to be about as unwanted or noisy as a boom having a rise time of 9.0 msec but a peak overpressure of 2.0 psf.

2. The relative effects of the spectral changes on judged noisiness are consistently predicted by the various units of sound measurement commonly used for evaluating typical subsonic aircraft flyover noises.

3. In order to best predict from physical measures the subjective noisiness of sonic booms when compared with the noise from subsonic aircraft, it appears necessary and appropriate to apply an "impulse" correction value to EPNL's measured or calculated for the sonic booms.

4. On the basis of the present study and previous tests conducted with sonic booms and subsonic aircraft noise heard outdoors, a graph of the functions for correcting PNLs of impulses for outdoor and indoor listening is tentatively proposed. The amount of impulse correction for a given sonic boom when heard indoors appears to be about one-half of that required for listening to the same boom outdoors.

In a previous study (see capsule summary HRSC-54) questions were raised concerning the validity of "controlled" experiments equating acceptability of booms and subsonic aircraft noise. However, the finding of the present investigation that the relative effects of spectral changes on the judged noisiness of sonic booms are consistently predicted by the various units of sound measurement commonly used for evaluating subsonic aircraft noise indicates that there is a definite relationship between the acceptability of the two types of sounds.

HRSC-83
ECONOMIC AND SOCIAL ASPECTS OF COMMERCIAL AVIATION AT SUPERSONIC SPEEDS
Bo. K. O. Lundberg
ICAS Paper No. 72-51, Presented at The Eighth Congress of the International Council of the Aeronautical Sciences, Amsterdam, The Netherlands, August 28 to September 2, 1972

This paper is basically the same as an earlier paper by Lundberg (see capsule summary HRSC-69). The reader is referred to the capsule summary of that paper.

HRSC-84
AN UNSTABLE STEERING TASK WITH A SONIC BOOM DISTURBANCE
K. W. Lips
UTIAS Technical Note No. 179, September 1972

The horn-type sonic boom simulation facility described in capsule summary SM-16 was used in the experiment described in this report to investigate the effect of sonic booms on an individual's compensatory tracking performance for an unstable system. Six subjects, ranging between the ages of 25 and 54, were exposed to simulated sonic booms having overpressures of 2, 4, and 8 psf, durations of 80 msec, and rise times of 3.0 msec. (The majority of the booms had overpressures of two psf.)

The tracking task resembled an unstable automobile driving task. A standard size auto steering wheel provided the subjects with a means of controlling the horizontal displacement of a moving vertical line (error signal) from fixed reference lines on an oscilloscope screen. Basically, it was the task of the driver to follow a random function which forced the error bar off center. Rather than providing direct position control, the task was made more challenging by having the wheel output (driver control) signal filtered through the dynamics of a first order linear unstable system.

The basic technique was to carry out three consecutive 150 sec runs with a two-minute rest period after each one. The subject was told that he may or may not be exposed to a sonic boom disturbance during the test.

For the purpose of comparison with sonic-boom response, an alternative stimulus was presented to the driver in the form of a question asked by the operator over the intercom. Except for the nature of the disturbance, the entire run procedure was identical with that used during sonic-booms.

The following are the main conclusions reached as a result of this experiment:

1. On the basis of the findings obtained during this study, it can be said that sonic-boom disturbances of the type generated by the Concorde SST result in a measurable startle effect (performance deterioration during a tracking task) manifesting itself in somewhat different ways for different individuals at different times.

2. Total performance loss as well as almost negligible change in performance were observed. Between these extremes was found a pattern involving an initial startle followed by peak amplitude response, sometimes partial recovery, and total recovery. This pattern, in general, is not similar to that obtained from startle following a simple question.

3. The problem of specifying a given response for a given sonic-boom signature and task appears to be statistical in nature.

It is pointed out by the authors that the results apply only to that particular task simulated during this study. Because of the small number of subjects and somewhat qualitative approach used in measuring reaction characteristics no "final" conclusions were felt to be justified. Rather, it was felt that the results provide a guide toward a potentially fruitful area of research into the effect of sonic-booms on human response.

HRSC-85
SONIC BOOM STARTLE: A FIELD STUDY IN MEPPEN, WEST GERMANY
D. N. May
Journal of Sound and Vibration, Vol. 24, No. 3, 1972, pp. 337-347

The results of a field experiment conducted in Meppen, West Germany are presented in this paper. The purpose of the experiment was to relate the subjectively-reported startle of up to 39 subjects exposed to up to 53 sonic booms to simple functions of their rise times and overpressures.

The booms were generated by Luftwaffe F-104G Starfighter aircraft flying at 36,000 feet and a speed of approximately M = 1.6. The measured overpressures were on the order of 1.5 psf. Rise time, which was defined simply as the time to peak overpressure, lay in a range as wide as 2 to 39 ms. The booms were applied approximately evenly over normal working hours on ten consecutive weekdays.

The subjects in the experiment were recruited at very limited notice, so that no representative cross-section of the population could be used. They fell into a number of occupational categories as follows: 4 laborers (average age 35), 15 schoolboys (average age 16), 20 scientific staff (average age 34). The subjects carried questionnaires with them, and mostly went about their normal lives during the experiment.

The questionnaires asked subjects to "imagine how much you are startled by a fairly loud door-slam, and suppose that that startles you by an amount which you value as 10. Then assign . . . a value in proportion to the amount the bang startles you . . .". The judgment was termed Startle Rating, S_R.

An analysis was then made to relate Startle Rating S_R to various functions of peak overpressure ΔP and rise time Δt. Preliminary prediction equations were found for the startle due to sonic booms heard outdoors as follows:

1. $S_R = 3.56\ (\Delta P^2/\Delta t) - 0.116\ \Delta t + 9.05.$

   with ΔP in lb/ft^2 and Δt in ms for the range

   $0.5<\Delta P<2.5$ and $1<\Delta t<40$.

2. $S_R = 1.55\ 10^{(L-100)/10} + 7.05$

   where L, the loudness of the boom in phons, lies in the range 90-115.

It is suggested by the author that the unit of startle rating be the "jump". From the first equation, it is pointed out that Concorde-type booms of about 2 lb/ft^2 nominal or ground-reflected overpressure could be expected to produce "jumps" ranging from about 5 through 10 to 16 as the rise time dropped from 40 ms to 2 ms, respectively. An unusually "severe" Concorde-type boom with an overpressure of about 2.5 lb/ft^2 and a rise time of 2 ms would produce 20 "jumps", and an unusually "gentle" boom with an overpressure of about 1.5 lb/ft^2 and a rise time of 35 ms would produce 5 "jumps".

In a parallel study conducted at the same time the present study was being made (see capsule summary TSC-46), May derived a simple relationship between rise time, overpressure, and loudness of a sonic boom.

It is pointed out by the author that there are good reasons for regarding the prediction equations only as preliminary ones. Due to the fact that the experiment was organized on only a few days' notice, the subject population was inadequately constituted and a proper experimental plan was impossible. The waveforms were not always those experienced at the subjects' ears. Furthermore, the data did not contain a very substantial number of judgments.

However, in spite of its limitations this was a significant investigation in that these results were the first to provide a means of relating startle to the boom parameters.

HRSC-86
AWAKENING EFFECTS OF SIMULATED SONIC BOOMS AND AIRCRAFT NOISE ON MEN AND WOMEN
J. S. Lukas
Journal of Sound and Vibration, Vol. 20, No. 4, 1972, pp. 457-466

This paper summarizes the research conducted at

Stanford Research Institute over the period 1966-1971 concerning the effects of sonic booms on sleep. The reader is referred to capsule summaries HRSC-40, HRSC-51, HRSC-53, HRSC-67, and HRSC-68 for details of these studies. The main points brought out in this review are the following:

1. Children 5-8 years of age are not affected by noise during sleep.

2. Older subjects are more sensitive to noise during sleep than are younger subjects.

3. Women are more sensitive than men to noise during sleep.

4. Individuals may vary widely within an age group with respect to their relative sensitivities to noise during sleep.

5. The frequency of behavioral awakening is a function of the intensity both in the case of sonic booms and in the case of subsonic jet flyover noise.

This paper is an updated version of the paper described in capsule summary HRSC-65. The earlier paper contains no information concerning the effects of sleep on women.

HRSC-87

BEHAVIORAL AWAKENING AND SUBJECTIVE REACTIONS TO INDOOR SONIC BOOMS

J. E. Ludlow and P. A. Morgan

Journal of Sound and Vibration, Vol. 25, No. 3, 1972, pp. 479-495

In this paper two experiments dealing with the effects of sonic booms on sleep are described. The first experiment was described in an earlier paper by Morgan and Rice (see capsule summary HRSC-56) and will not be covered in depth here. The reader is referred to the capsule summary of that paper for details. The second experiment was similar to the first except that the simulated sonic booms covered a wider range of intensities and the length of the experiment was fourteen nights instead of six nights.

In the second experiment eight subjects spent a total of fourteen consecutive nights in the bedrooms. The first six nights were for adaptation, and, of the remaining eight nights, two were control nights and six were used for sonic boom exposure. The main reason for the greater length of the second experiment was to allow the subjects more time to adapt to the unfamiliar surroundings. The stimulus used throughout both experiments was a recording taken from a sonic boom simulator which was intended to represent a reasonable facsimile of an indoor sonic boom.

The second experiment resulted in the following findings:

1. Over the six "adaptation" nights there was a general, but not significant, tendency towards a decrease in spontaneous awakenings.

2. Of the total of 59 spontaneous awakenings for the entire group over the first six nights, 34% occurred in the first half of the night.

3. As the experiment progressed, subjects were awake on fewer occasions when stimuli were presented, and they awoke in response to fewer stimuli.

4. As the nights progressed, subjects were able to return to sleep more rapidly after being aroused by the simulated booms.

5. In the second experiment, in which the range of stimulus intensities used was greater than in the first experiment [69, 79 and 84.5 dBA (fast) vs. 71.2, 74.2 and 77.6 dBA (fast)], it was found, in contrast to the findings of the first experiment, that the stimulus intensities did affect behavioral awakening.

Previous investigations of the effects of sonic booms on sleep were conducted by Lukas and Kryter (see capsule summaries HRSC-40 and HRSC-53), Lukas, Dobbs, and Kryter (see capsule summary HRSC-68), Smith and Hutto (see capsule summary HRSC-80), and Chiles and West (see capsule summary HRSC-78).

HRSC-88

FACTORS AFFECTING COMMUNITY ACCEPTANCE OF THE SONIC BOOM

Harvey H. Hubbard and Domenic J. Maglieri

NASA TMX-905, Proceedings of NASA Conference on Supersonic-Transport Feasibility Studies and Supporting Research, December 1963, pp. 399-412

This paper presents a brief review of sonic boom phenomena and factors affecting community acceptance of sonic booms. Results obtained in conjunction with various flight test studies concerning the reactions of observers and damage complaints received are discussed. It is concluded that although the experience with military aircraft was in the range of overpressures of interest, it was not definitive enough to make a quantitative evaluation of the problem. However, the experience with military aircraft did indicate that a major factor in shaping attitudes toward sonic booms is the matter of building vibrations.

HRSC-89

SONIC BOOMS RESULTING FROM EXTREMELY LOW-ALTITUDE SUPERSONIC FLIGHT: MEASUREMENTS AND OBSERVATIONS ON HOUSES, LIVESTOCK AND PEOPLE

C. W. Nixon, H. K. Hille, H. C. Sommer, and E. Guild

Aerospace Medical Research Laboratories, Wright-Patterson A.F. Base, Ohio, Report No. AMRL-TR-68-52, October 1968

In the flight-test experiment described in this report, sonic booms generated by F-4C aircraft flying low-level terrain-following profiles during Joint Task Force II operations near Tonopah, Nevada, were recorded under and near the flight tracks, and responses of structures, people, and animals were observed. The overpressure levels directly under the flight track varied between 80 and 144 psf. Only the human response findings will be discussed here. For a discussion of the animal response and structural response results, see capsule summaries AR-4 and SR-46, respectively.

Bioacoustics personnel operating the main recording station were exposed to sonic booms ranging in peak overpressure from 50 psf to 144 psf. Ear

protection was worn by some individuals only during the first few runs, while others did not use ear protection at any time. The pressure wave was felt by the head and body during boom exposures as a jarring sensation. Rather strong tactile and kinesthetic stimulation were experienced as well. Some momentary discomfort, fullness, and ringing of the ears were experienced with the more intense booms and these persisted from periods of a few seconds to as many as 60 to 120 seconds. For the most intense booms the symptoms of fullness, ringing, etc., were significantly greater in the ear facing the approaching aircraft than in the contralateral ear. Symptoms were essentially the same for both ears for the lesser intense booms.

No distinct auditory pain was reported although some booms were described as very sharp. Personnel further commented that the most intense booms would have been judged to be painful had they been any greater in magnitude. From this it was concluded that the threshold of pain for these individuals and kinds of exposures was close to but still greater than 144 psf. Although hearing acuity was not physically measured, subjects reported no indication of any observable symptoms of temporary hearing loss or other ear involvement.

Individuals performing routine tasks of photography and operation of the electronic equipment were required to visually follow the aircraft during its supersonic pass. Although task performance was not interrupted or bothered, all personnel expressed avoidance behavior consisting of involuntary ducking and flinching in response to the booms. This behavior occurred for individuals with as well as without ear protection. Startle responses to the actual pressure wave also occurred. This behavior did not habituate during the three-day flight program. In fact, involuntary tensing or muscle set of the body in anticipation of the booms appeared to be stronger for the later exposures than during the initial booms.

Ages of exposed individuals at various occupied locations varied from 6 to more than 70 years. At these locations the magnitudes of the overpressures were less than at the main recording station but still much greater than boom levels normally experienced. No physiological symptoms or effects of the sonic booms were found in these people.

The overpressure levels experienced in this investigation were much greater than in any previous or subsequent investigations. The fact that no physical harm resulted from these extremely intense booms provided very strong evidence that the levels of sonic booms normally experienced (below about 2 psf) are not a health hazard to humans.

HMSC-90
FREQUENCY SPECTRUM OF N-WAVES WITH FINITE RISE TIME
P. B. Oncley and D. G. Dunn
The Journal of the Acoustical Society of America, Vol. 43, No. 4, 1968, pp. 889-890

This is a short note which compares the frequency spectrum of an N-wave with finite rise time to that of an N-wave having zero rise time. It is shown that, while the pressure spectrum of an N-wave with zero rise time is a published spherical Bessel function, the spectrum with a finite rise time not exceeding one-tenth of the duration of the N-wave can be closely approximated by multiplying two spherical Bessel functions, or, equivalently, by adding their logarithmic curves. The result is that the finite rise time effectively acts as a fairly good low pass filter with a cutoff at a frequency represented by 1/R (here R is the rise time), with a very minor contribution from the higher lobes.

HMSC-91
REPORT ON THE SONIC BOOM PHENOMENON, THE RANGES OF SONIC BOOM VALUES LIKELY TO BE PRODUCED BY PLANNED SST'S, AND THE EFFECTS OF SONIC BOOMS ON HUMANS, PROPERTY, ANIMALS, AND TERRAIN
Attachment A of ICAO Document 8894, SBP/II, Report of the Second Meeting of the Sonic Boom Panel, Montreal, October 12 to 21, 1970

This report is composed of six chapters, each dealing with a certain aspect of sonic boom phenomena. The present capsule summary summarizes only Chapter 3, which is entitled "Sonic Boom Effects on Human Beings."

The discussion presented in Chapter 3 is in the form of a summary of the state of knowledge concerning human response to sonic booms. The following are some of the conclusions reached as a result of the review of laboratory and flight studies of human response:

1. Individual human response to an individual sonic boom is highly variable because of personal and sociological factors: hence, it is not very predictable. The response of a collection of human beings to an individual sonic boom plays down these variable factors by averaging over them. Promising prediction methods based on features of the particular boom signature are evolving, although they are not fully verified. The response of a collection of human beings to a collection of sonic booms involves further averaging over the boom signature variability from place to place and time to time outdoors and indoors for given flight conditions (given nominal peak overpressure). Such collective human response is to some measure predictable from community surveys.

2. The effect of the scatter in measured overpressure intensities due to the atmospheres is automatically included in community surveys.

3. Outdoor annoyance increases markedly as shock rise time decreases, as well as with the degree of "spikiness" in the signature.

4. Indoor annoyance depends upon many factors in addition to the loudness level, such as the degree of rattle and vibration and whether the individual is a home owner.

5. For an individual flight the only feature subject to a degree of control is the flight profile and, therefore, the nominal peak overpressure (and other parameters)

that may be calculated as characteristic, on the average, of that flight profile. Thus collective human response measured against nominal mean overpressure--obtained from community surveys--is probably the most pertinent indicator of public response to the sonic boom at a given boom frequency.

6. The body of data on community response to the sonic boom lacks adequate information pertaining to boom frequency and to night-time sonic boom exposure as well.

This is one of the best summaries available concerning the state of knowledge of human response to sonic booms.

HRSC-92
A POTENTIAL DESIGN WINDOW FOR SUPERSONIC OVERFLIGHT BASED ON THE PERCEIVED LEVEL, PLdB AND GLASS DAMAGE PROBABILITY OF SONIC BOOMS
Thomas H. Higgins and Larry K. Carpenter
FAA Report, July 1973

This paper presents an investigation into the possibility of determining a combination of overpressure and rise time which results in an "acceptable" sonic boom. The key to this investigation is the following general formula for estimating the perceived level of a sonic boom:

Perceived Level (PLdB)=55+20 $\log_{10}\Delta P/\tau$

where ΔP is the sonic boom overpressure in psf and τ is the rise time in seconds. This formula is based upon subjective ratings of sonic booms obtained during the Edwards Air Force Base experiments of 1967 (see capsule summary HRSC-28).

The results of a sonic boom simulation experiment are presented which show that a sonic boom level of 108 PLdB was acceptable to 75 percent of the subjects tested and a sonic boom of 100 PLdB was acceptable to 95 percent of the subjects. Based upon this data and data concerning the potential of sonic booms for causing glass damage, curves are presented which show combinations of overpressure and rise time which will result in acceptable sonic booms. This "design window" includes overpressures as high as 5 psf.

Two areas needing additional work are pointed out:

1. Psychophysical studies regarding human acceptability of the sonic boom perceived level.

2. Aerodynamic studies regarding overpressure/rise-time reduction and controllability techniques with a view to reducing the perceived level, PLdB, of civil supersonic transport.

This paper does a good job of emphasizing the importance of taking both overpressure and rise time into account when airplane design studies are being conducted.

6.0 STRUCTURAL RESPONSE

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SR-1

AIRPLANE MOTIONS AND LOADS INDUCED BY FLYING THROUGH THE FLOW FIELD GENERATED BY AN AIRPLANE AT LOW SUPERSONIC SPEEDS

G. H. Jordan, E. R. Keener, S. P. Butchart

NACA RM H57D17a, June 7, 1957

The results of an investigaton of airplane motions and loads induced by flying through the flow-field of an airplane at low supersonic spe ds is presented in this report. These results indicate that significant airplane motions and vertical-tail loads can be experienced as a result of close-proximity side-by-side passes in the same direction at supersonic speed. The most severe motions and vertical-tail loads were experienced d: 'ng passes made at separation distances less than 100 feet and at a time to pass near and slightly greater than the airplane natural period in yaw. The passing airplane experienced maximum sideslip angles of about 5.4° and maximum vertical-tail loads of approximately 50 percent of design limit in shear, bending moment, and torsion. Increasing the lateral separation distance was shown to decrease the maximum sideslip angle and, thus to reduce the maximum vertical-tail load.

A later investigation reported by Maglieri and Morris (see capsule summary SR-4) showed that the response of light airplanes to sonic booms of the order of 1-16 psf is negligible. These results do not contradict those of the present report, since the overpressures involved were much higher and the exposure time was considerably longer (both airplanes flying at approximately the same speed) in the present investigation.

SR-2

TACTICAL USE OF SHOCK WAVES FROM AIR-CRAFT

W. H. Young

Bureau of Aeronautics, Navy Dept., Washington, D.C., Report No. DR 1808, April 1958

The possible tactical use of the sonic boom produced by supersonic aircraft is considered in this paper. The effects upon light structures, camouflage, and helicopters on the ground and in the air were examined. It is found that some damage to light structures is probable, but damage to aircraft is improbable. The airplane must be flown within a few hundred feet of its target to be effective. It is concluded that the shock wave attack may prove useful against secondary targets and targets of opportunity after delivering an attack using "live" ammunition against a primary target. It is also concluded that the harassment of personnel by low flying supersonic aircraft should be considerable.

A later flight test investigation reported by Maglieri and Morris (see capsule summary SR-4) showed that the response of light airplanes to overpressures of 1-16 psf was negligible. Another investigation reported by Jordan, et al (see capsule summary SR-3) showed that C-47 airplanes exposed to sonic boom overpressures up to 140 psf experienced very little damage. These findings agree with the conclusions of the present report.

SR-3

FLIGHT MEASUREMENTS OF SONIC BOOMS AND EFFECTS OF SHOCK WAVES ON AIRCRAFT

G. H. Jordan

Society of Experimental Test Pilots, Quarterly Review, Vol. 5, No. 1, 1961, pp. 117-131

This paper presents a discussion of flight measurements of sonic booms and the effects of shock waves on aircraft. Only the discussion of the latter effects will be summarized here.

The results of a previous investigation (see capsule summary SR-1) concerning airplane motions and loads induced on an airplane flying through the shock wave system generated by another airplane are summarized in this paper. The reader is referred to the capsule summary of the earlier paper for a discussion of those results.

Also discussed are the results of a flight-test experiment whose purpose was to determine whether or not shock waves can damage a C-47. The C-47 was subjected to overpressures as high as 140 lb/sq. ft. Tests were conducted both with the C-47 on the ground and in a landing condition approach. During the ground tests the maximum response of the wing to the most intense shock waves was approximately 5 percent of design load limit. The only damage to the C-47 during all of the ground tests was loosening of the sealing fabrics on the rear spars of the horizontal and vertical tails, and breaking of a cast-aluminum bracket holding a fire extinguisher in the passenger cabin. Several inspection doors on the lower surface of the wing were opened by the shock pressures during passes at the lowest altitudes.

In the landing-approach condition the response of the airplane appeared to be much less severe than for similar passes with the C-47 on the gound. No control problems were experienced by the pilot, and the C-47 was not damaged.

It is concluded that a supersonic transport should experience no difficulty nor be a cause of concern to other airplanes if normal separation distances are maintained.

A later flight test investigation reported by Maglieri and Morris (see capsule summary SR-4) showed that the effects of sonic boom of 1-16 lb/sq. ft. on light aircraft was negligible.

SR-4

MEASUREMENTS OF THE RESPONSE OF TWO LIGHT AIRPLANES TO SONIC BOOMS

D. J. Maglieri, G. J. Morris

NASA TN D-1941, August 1963

The results of an investigation whose purpose was to measure the acceleration responses of a Piper Colt and a Modified Beech C-45H to sonic boom overpressures varying from about 1 to 16 psf are presented in this paper. The airplanes were exposed to the overpressures while parked on the ground, in cruising flight, in turns, and in flight near stall.

Acceleration increments measured near the center of gravity were less than $\pm$ 0.2g in the normal, transverse, or longitudinal direction, had periods of about 0.1 second, and generally were damped out in less than two cycles. Some responses to the booms were not discernible from the residual acceleration level. Airplane rigid-body motions were not detected from motion pictures and the primary source of the response was thought to be structural. Somewhat higher responses were measured for the Piper Colt than for the Modified Beech C-45H and were attributed to the lighter wing loading of the Colt.

In general, the magnitude of the acceleration response increased with overpressure, was dependent on the orientation of the shock wave and test aircraft, and apparently was somewhat higher in flight close to stall than in cruise or turning flight.

It is concluded that the responses to the sonic booms appeared to be so small as to be insignificant as regards structural loads or airplane control and were, for the most part, negligible in comparison with responses resulting from routine operations such as take-off, landing, and flight in light air turbulence.

Three previous investigations dealt with the effects of sonic booms on aircraft. The earliest, which was by Jordan (see capsule summary SR-1), indicated that significant airplane motions and vertical tail loads can be experienced as a result of close-proximity side-by-side passes at supersonic speed. The second, by Young (see capsule summary SR-2), found that damage to aircraft as a result of sonic booms is improbable. The third, by Jordan (see capsule summary SR-3) again, demonstrated that the damage to C-47s as a result of sonic boom overpressures up to 140 psf is very minor. The results of the present investigation do not contradict any of these earlier results.

SR-5
SOME SONIC-BOOM-INDUCED BUILDING RESPONSES
J. M. Cawthorn
Journal of Acoustical Society of America, Vol. 35, No. 11, 1963, pp. 1886, 1887

This paper presents the results of a series of tests in which a building structure instrumented with microphones, strain gauges, and accelerometers was subjected to sonic booms. The significance of variables such as aircraft Mach number, altitude, and flight direction is discussed. Included in the discussion are shock wave pressure loading time histories and the associated transient responses of various building components. The measured stress levels associated with the range of sonic boom overpressures estimated for routine military and commercial operations are noted to be relatively small as compared to the design stresses of the building. It is also noted that they may be of the same order of magnitude as those associated with such everyday occurrences as door slamming.

SR-6
SONIC BOOM EFFECTS ON LIGHT AIRCRAFT, HELICOPTERS AND GROUND STRUCTURES
Office of SST Dev. F.A.A.
J. K. Power
for Presentation American Society for Testing and Materials, June 25, 1964

This paper reviews the results of two different investigations conducted to determine the effects of sonic booms on light aircraft, helicopters, and ground structures. These investigations were: (1) the measurements of the response of light aircraft and helicopters to sonic booms as reported by Maglieri and Morris (see capsule summary SR-4), and (2) the Oklahoma City flight test program (see capsule summary SR-12).

The following conclusions were reached as a result of the Oklahoma City program:

1. The deflection of the main structural elements resulting from the booms was negligible.

2. No wooden structural member of the test house had been stressed beyond an increment of approximately 29 PSI beyond static condition. Permissible working stress is about 1,100 PSI.

3. The closing of the garage door, the front door, or raising the attic stairs in the garage can cause strains (stresses) in key structural members equal to those caused by the sonic booms.

4. The natural frequencies of all instrumented structural elements can easily be measured from the strain records, and may be used to determine cumulative effects, if any.

5. As expected, the strains and accelerations recorded were generally less for the .68 psf boom than for the .96 psf and 1.93 psf booms, but not in every case.

6. The reverberation times of some elements in the houses were as long as several seconds.

7. The overpressures resulting from the Oklahoma City flight tests did not cause breakage of good quality, properly installed window glass. However, these overpressures may have the capability of triggering cracking or breaking glass that contained residual stresses induced by improper installation, building settlement, previous damage, or poor quality.

8. The overpressures may have the capability of triggering plaster cracking within a stressed portion of plaster.

9. The overpressures of the magnitude encountered in the test flights ($\leq$ 2 psf) were not of sufficient magnitude to cause primary structural damage to well-constructed and well-maintained buildings.

10. No damage occurred to any furnishings, appliances, or any other object in the four test houses.

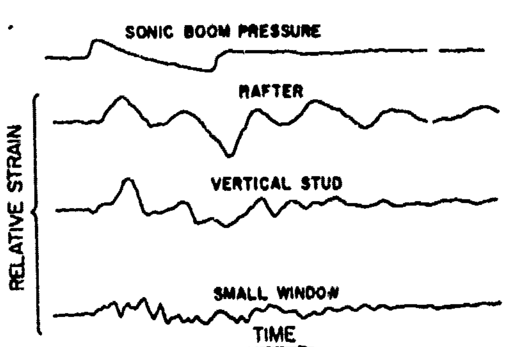
11. The flight test program to study light airplane responses indicated that exposure to sonic boom of 1.0 - 16.0 psf resulted in a pilot reflex generally limited to an eye blink. These overpressures did not in any way significantly affect the aircraft control, structure, displays, or pilot's observable reaction.

This is a good summary of the state of knowledge as of 1964 concerning the effects of sonic booms on structures.

SR-7
EFFECTS OF SONIC BOOM AND OTHER SHOCK WAVES ON BUILDINGS
W. H. Mayes and P. M. Edge, Jr.
Materials Research & Standards, Vol. 4, No. 11, Nov. 1964, pp. 588-593

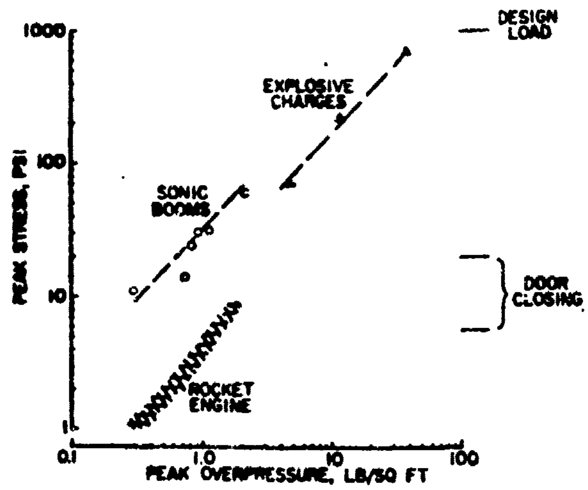
This paper presents some response data for a building exposed to sonic booms and other types of excitation. Several supersonic flights were made over an instrumented building which had a flat roof and dimensions of approximately 20 by 40 by 10 feet. The range of sonic boom exposures was 0 - 3 psf. The same building was exposed to loadings from various explosive charges about 1/4 mile away and also to acoustic loading during the launch of a rocket (100,000-lb. thrust) about 1/2 mile away.

The figure below shows the strain-time histories for a rafter, a vertical stud, and a small window due to excitation by the pressure signature illustrated at the top. It can be seen that the transient responses last for a longer period of time than the sonic boom pressure signature and each has its own characteristic response. In the case of the rafter trace the maximum peak strain value did not occur during the initial onset of load. In this case, the negative pressure peak of the sonic boom arrived in phase with the motion of the rafter and thus resulted in an increased strain. However, in the case of the stud the opposite effect occurred, and the resulting strains were relatively less. Thus the transient strain responses of each component of the building structure depends on its own vibration characteristics and on the type of loading.



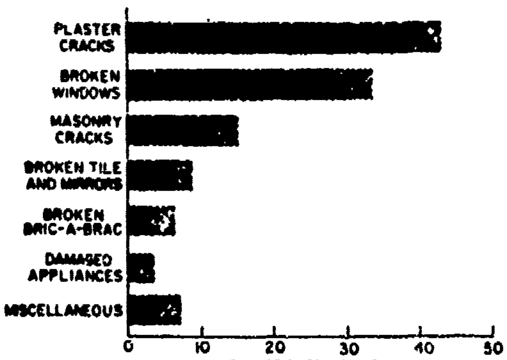
Sample strain-time histories for components of a building exposed to sonic boom

The figure below shows the peak values of the measured strains in a vertical stud due to various types of loading. Peak stress values are shown for sonic boom overpressures from 0.3 - 3 psf, and the maximum stress is about 60 psi. This is stated to be small compared to the design live-load stresses for the building. It is of the same order of magnitude as the stress induced by such a common occurrence as door closing. Also shown are data for the explosive charge and rocket noise loadings. It is tentatively concluded from these results that there should be no concern for damage to primary structures due to sonic boom pressures in the range shown.



Peak vertical stud stresses as a function of peak overpressure for various types of excitation

The above conclusion is consistent with Air Force records of damage complaints due to sonic booms as shown in the figure below, which was taken from this paper. This figure shows that the reported damage refers directly to the secondary structure of the building, and in particular to brittle surfacings for which the primary failure mode is tension in the surface.

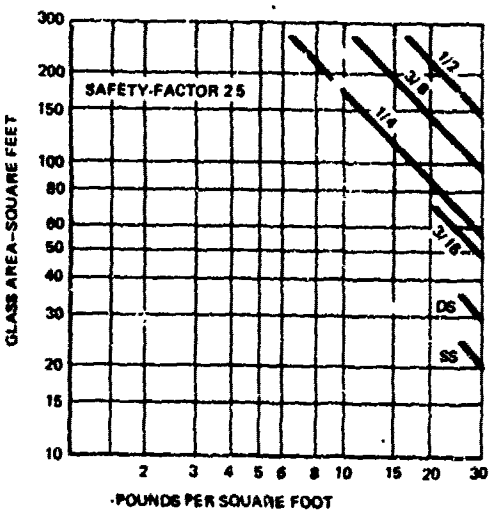


Classification of about 3000 complaints due to sonic booms as recorded in Air Force File

The conclusions reached in this investigation agree with those reached in the more extensive Oklahoma City sonic boom tests (see capsule summary SR-12).

SR-8
RESPONSE OF GLASS IN WINDOWS TO SONIC BOOMS
R. W. McKinley
Materials Research & Standards, Vol. 4, No. 11, November 1964, pp. 594-600

The response of window panes to sonic booms is treated in this paper. Most of the discussion is centered around relating the loading on the glass to the thickness required for a given breakage safety factor. The figure below, which was taken from this paper, but which is based on the work of L. Orr ("Engineering Properties of Glass," BRI-NAS-NRC Publication 478, Bldg. Research Inst., NAS-NRC, 1957), shows the recommended thickness (in inches) of plate and window glass to resist sonic boom pressures. The safety factor of 2.5 means that the probable number of panes which will break at initial occurrence of design load for each 1,000 loaded is 8.



Recommended thickness of plate and window glass to resist sonic boom pressures

In a later paper (see capsule summary SR-21) Wiggins presents a chart similar to the one above. The results of that chart are much more conservative than for the chart above because Wiggins based his chart on a predicted or measured average ground overpressure that took into account the variability in overpressure that can arise from a given aircraft flying at a given altitude. The maximum overpressure within three standard deviations of the mean overpressure was chosen as the standard. The result is that Wiggins' chart gives overpressure levels for which there is only a 1/100,000 chance that damage could occur, as compared to 8/1000 for the present chart.

SR-9
MEASURING THE SONIC BOOM AND ITS EFFECT ON BUILDINGS
C. W. Newberry
Materials Research & Standards, Vol. 4, No. 11, November 1964, pp. 601-611

In this flight test experiment an English Fairey Delta was used to generate sonic booms having intensities between 2 and 5 psf. The roofs and walls of two buildings instrumented with accelerometers and shock pressure gauges were subjected to the sonic booms. One of these buildings was quite old, though apparently structurally sound. The other was fairly new and in good condition. The object of these tests was to correlate the parameters of a sonic boom with the vibration effect on a building and at the same time to measure the maximum shock pressure to which the building might have been subjected had it been at the focus of the boom. The latter objective was not achieved, however, since the focused shock pressure eluded measurement.

The following tentative conclusions were reached as a result of this investigation:

1. Sonic boom pressures of about 5 psf produced accelerations of about 1.0 g in a typical slated roof and about 0.6 g in a heavy tiled roof. The former is approaching the condition at which rattling of the slates might occur.

2. Resonances can occur between the sonic boom impulses and a typical house structure. This increases the vibration beyond what would ensue from a simple shock at a comparable pressure. These resonances are not likely to be severe except possibly at a f.. discrete points in the boom area. The probability of damage in country areas is, therefore, quite small, since the chance that one of these discrete points in the boom area will coincide with a building is small.

3. Should a focusing boom of the type produced in these tests impinge on an extensive built-up area, the probability of a coincidence between the focus zone and a building, or between an optimum resonance point and a building is very high, if not a certainty. It would appear that some damage might be expected, particularly to roofs.

The overpressures involved in the present investigation were slightly larger than those of the Oklahoma City sonic boom tests (see capsule summary SR-12) or the investigation reported by Mayes and Edge (see capsule summary SR-7). However, since the present investigation was not as extensive as the other two (in particular the Oklahoma City tests), it is not possible to determine the difference between structural response at the higher overpressures and that at the lower overpressures.

SR-10
SOME RESULTS OF THE OKLAHOMA CITY SONIC BOOM TESTS
J. K. Power
Materials Research & Standards, Vol. 4, No. 11, November 1964, pp. 617-623

This paper is a modified version of the paper summarized in capsule summary SR-6. The present paper discusses only the results of the Oklahoma City sonic boom tests and not the effects of sonic booms on light aircraft and helicopters. The reader is referred to the capsule summary of the earlier paper for a discussion of significant findings.

SR-11
DAMAGE TO OTTAWA AIR TERMINAL BUILDING PRODUCED BY A SONIC BOOM
W. A. Ramsay
Materials Research & Standards, November 1964, pp. 612-616

This paper discusses the damage caused to the Ottawa air terminal building on August 5, 1959, when an F-104 fighter made a low altitude flight over the building and accidentally exceeded the speed of sound. The altitude of the plane was about 500 feet when it passed over the building. Construction of the building was 98 percent completed at the time of the incident.

The cost of repairs to the Canadian government was about $300,000, of which glass, curtain wall, and associated work cost $180,000. The following conclusions were reached regarding the observed damages:

1. Smaller glass panes suffered least damage.

2. Rooms open to the outside air were less susceptible to damage.

3. Shielding reduced damage.

4. Standard built-up type roofing was susceptible to damage.

5. There was no apparent damage to floors, marble wall facings, metal partitions, doors, hardware, or plumbing.

Due to the fact that this was an accident there were, of course, no overpressure measurements available. However, due to the extremely low altitude of the plane, the overpressure levels were probably in excess of 150 psf. Hence the damage levels of this incident are much greater than any that would ever occur due to an airplane flying at normal altitudes.

SR-12
FINAL REPORT STRUCTURAL RESPONSE TO SONIC BOOMS
Office of Deputy Administrator for SST Dev. F.A.A., Washington, D. C., SST 65-1, Vol. 1, AD 610822, February 1965

The purpose of this report is to document and report on the results of a study of the structural response of some typical residential structures in a typical community to an extended series of controlled sonic booms which varied in magnitude between 0 and 3.5 psf. The 39-week test program was conducted in Oklahoma City and consisted of twenty-six weeks of eight daily, controlled sonic booms, followed by thirteen weeks of observation and inspection of the structures to determine the rate of normal deterioration as compared to the rate of deterioration found during the 26-week sonic boom period.

The test structures consisted of a total of eleven typical types of residential structures, eight of which were located within five miles of the regular flight path, one of which was located ten miles from the flight path, and the remaining two located about twenty-five miles from the flight path at Norman, Oklahoma, which was beyond the sonic boom area. Each of these residences was instrumented with strain gages and accelerometers at various strategic locations, such as windows, ceiling joists, wall studs, doors, etc.

Total defects found during the 13-week inspection period, after the booms had ended, were considerably less than the defects found during the 26-week boom period, as would be expected since the inspection period was only half the sonic boom time period. However, in Test Houses 1, 2, 3, and 4, which were all located within five miles of the flight track, the total interior defects were more than twice as great for the 26-week sonic boom period as for the 13-week inspection period. Specifically, Test House No. 1 had a total of 282 interior defects during the 26-week boom period, but only a total of 99 found for the 13-week inspection period (a ratio of almost three to one); Test House No. 2 had comparable totals of 261 and 56, respectively, for the two periods (a ratio of 4-1/2 to 1); Test House No. 3 had comparable totals of 432 and 77, respectively, for the two periods (a ratio of about 5-1/2 to 1); and Test House No. 4 had comparable totals of 509 to 134, respectively, for the two periods (a ratio of about 4 to 1). It was found that in each of these four houses the rate of paint cracking and miscellaneous defects declined more rapidly than did the rate of nail popping. For example, the 282 interior defects found in Test House No. 1 for the boom period were about evenly divided between popped nail heads and the other defects, but during the non-boom period, popped nails represent 75% of the total of 99 defects found.

The following conclusions were reached as a result of the observations made during this investigation:

1. Conclusive evidence of significant damage to the test houses was not produced by this investigation. However, the significant increase in occurrence of minor paint cracking over nail heads and in corners in two of the test houses during the sonic boom period suggests that sonic booms accelerated this rather minor deterioration.

2. Controlled sonic booms of the magnitude and type produced in this program constitute a potential hazard to an indeterminate number of sub-standard or improperly installed glass installations.

3. Maximum free ground overpressure alone is of little value in making structural response calculations since the shape of the wave, and the length of the wave acting on the structure, plus the natural frequency of the structural element must be taken into consideration.

4. For a given aircraft producing N-waves of constant length, the impulse of the wave can be more closely correlated with some structural responses than can overpressure. However, impulses from one aircraft should not be directly compared with impulses produced by a dissimilar aircraft for purposes of structural response.

5. For purposes of structural response, impulse measurement should include both positive and negative phase portions of the sonic boom signature.

Several earlier investigations were conducted concerning the response of buildings to sonic booms (see capsule summaries SR-7 and SR-9), however none of these were as extensive as the present investigation. A very extensive investigation of structural response to sonic booms was conducted at White Sands, New Mexico in 1965. That test, while just as extensive as the present one, had a different purpose. The purpose of the present test was to determine the rate of deterioration found during the 26-week sonic boom period, while the purpose of the White Sands experiment was to determine sonic boom overpressure damage index levels associated with various types of structural materials.

The Edwards Air Force Base sonic boom experiments (see capsule summary SR-39) had overpressures in the 2-3 psf range. The general objective of the structural response portion of that experiment was to determine the response of typical structures to sonic booms having different signature characteristics in addition to making an evaluation of the damage resulting from the overflights of the XB-70, B-58, and F-104. That experiment, along with the present one and the White Sands tests, are the most extensive that have been conducted concerning structural response to sonic booms.

SR-13
FINAL REPORT STRUCTURAL RESPONSE TO SONIC BOOMS
Office of Deputy Administrator for SST Dev. F.A.A., Washington, D. C., SST 65-1, Vol. 2-Appendix, AD 610823, February 1965

Volume 1 of this report (see capsule summary SR-12) presents the results of a study of the structural response of some typical residential structures in Oklahoma City, Oklahoma to an extended series of controlled sonic booms. That volume discusses details of the test houses, instrumentation, test flights, results, and conclusions reached. The present volume consists of the appendix to Volume 1. It contains additional details concerning the test house inspection program, tabulations of the measured dynamic responses of the various structural elements, and weekly summaries of overpressure.

SR-14
GIANT SONIC BOOM CAUSES ONLY MINOR DAMAGE TO HOUSES
E. C. Shuman
Materials Research & Standards, Vol. 5, No. 2, February 1965, pp. 79-80

This is a brief article describing the damage that occurred as a result of an accidental sonic boom of 38 psf. The incident occurred at the White Sands Missile Range in New Mexico on Dec. 2, 1964 during a sonic boom demonstration for the press and other interested persons. The incident resulted from a low-level pass of an F-104, made at the request of photographers, during which the pilot unintentionally exceeded the speed of sound.

The following damage resulted from this intense sonic boom:

1. Two plate glass windows were shattered. These were each about 8 by 10 feet and only 7/32 in. thick. There was no evidence of large pieces of glass flying any distance, and the small pieces lay in approximately equal piles inside and outside the building.
2. About 15 panes in a greenhouse were shattered.

This incident is also discussed in the report covering the sonic boom tests at White Sands, New Mexico (see capsule summary SR-16).

SR-15
TEST SUPPORT TO F.A.A. SONIC BOOM TEST NEW MEXICO
M. Adams, R. McMullin
Boeing Document D6-17485, March 1965

The Boeing Company supplied instrumentation engineers and equipment for test operations in New Mexico during the January-February 1965 time period. These tests were conducted by the Federal Aviation Agency in conjunction with the National Sonic Boom Structural Response Program.

This report presents the test operations and details of the instrumentation systems. Six pressure measuring systems plus a direct read-out oscillograph were installed by Boeing at the test site. Sonic booms were generated by F-104 and B-58 aircraft flying at specified Mach numbers, altitudes, and flight headings over the test site. Of the total 878 booms produced, Boeing participated in 754 and averaged 99% recordings.

Representative samples of the oscillograph data traces are included in this report. Analysis and interpretation of these data were not within the scope of this report.

SR-16
STRUCTURAL REACTION PROGRAM NATIONAL SONIC BOOM STUDY PROJECT
John A. Blume & Associates Research Div., SST Dev., F.A.A., Report No. SST 65-15, Vol. 1, April 1965

This report presents the results of a study of the effects of sonic boom at varying levels of overpressure on selected structures and materials conducted at the White Sands Missile Range, New Mexico, from November 18, 1964, through February 15, 1965. The primary over-all objective of the study was a determination of sonic boom overpressure damage index levels associated with various types of structural material such as plaster, glass, and masonry.

F-104 and B-58 aircraft were used to generate 1433 and 61 booms, respectively. The daily flight schedule provided, in most cases, for 30 runs during a six-hour period. Scheduled sonic boom overpressures ranged from 1.6 to 19.0 pounds per square foot. The maximum overpressure recorded during scheduled study operations was 23.4 psf. An unscheduled boom of approximately 38.0 psf was flown during a demonstration for members of the press.

Sonic booms and structural-material reactions were measured with various instruments. Accelerometers, velocity transducers, seismometers, strain gages, pressure transducers of two types, and scratch gages were used.

The structural test area included 21 structures varying in design, construction, and age. Nine of these comprised the range camp prior to the program. Seven were constructed for the study, and five were old ranch houses or range structures within the boom area.

The following conclusions were reached as a result of this study:

1. The direction of boom wave propagation in relation to the orientation of a structure or element therein is very important to its reaction. For example, booms traveling directly into a window cause the window to react more violently than do booms traveling away from the window.

2. The peak pressure and signature of a boom recorded by a microphone at the center of an outside wall in general represents the peak loading on the entire wall surface.

3. The peak pressure recorded on an exterior wall surface is influenced by the wall rigidity. The stiffer the wall, the higher the pressure.

4. Reflecting surfaces such as billboards or houses placed beyond 15 feet from an external house wall do not significantly modify the peak boom pressure applied to the wall. Depending on orientation of the wall and the reflecting surface with respect to the aircraft vector, an increase in peak pressure can be expected when the reflecting surface is closer than 15 feet from the wall. The magnitude of the increase was not precisely known.

5. Boom-caused cracks, other than those caused by the highest overpressures, were found to be hairline in size and could be detected only on very close examination. This resulted from the fact that virtually no permanent distortion of the buildings was caused by booms of strength lower than about 24 psf.

6. Motion of the frame holding a window does not significantly influence the response of large windows framed by stud walls.

7. The average transmissibility of large windows (8' x 10'), defined as the ratio of peak inside to outside pressure, can vary between 0.5 (boom wave directed into window) and 1.0 (boom wave directed away from window).

8. The transmissibility of a room appears to be governed more by the size of the windows walling the room than by room volume.

9. Booms cause exterior walls to move more than interior walls in the bellows mode of vibration.

10. Winds do not have a strong influence on boom strength.

11. The average ground reflectivity coefficient is very nearly 2.0.

12. Sheer distortion rather than bellows distortion governs the minimum damage index level for walls in houses of the size used in the test. Bellows distortion may govern wall damage for larger houses, but the associated minimum damage index level for the larger houses could be higher than that observed in these tests.

13. To study the cumulative effects of repeated sonic booms, 680 successive flights at a scheduled overpressure of 5.0 psf were generated by B-58 and F-104 aircraft during one period of the study. No damage to previously undamaged material was identified during this period. Paint chipped at the edges of a previously damaged ceiling, and a badly pre-cracked window was damaged further. However, the additional damage in both of these cases was judged to be the result of sonic booms that exceeded minimum damage index levels rather than cumulative effect. No plaster cracks or crack extensions were observed as a result of the succession of 5.0 psf booms. Neither nail popping nor motion damage to bric-a-brac or other lightweight furnishings occurred during this period.

14. Bricks on the sill below the picture window in the two-story structure were cracked by the 38.0 psf sonic boom. This was apparently caused by the window flexing outward after being pushed inward by the boom overpressure (the glass was not damaged). No other brick damage could be attributed to the programmed booms.

In addition to the above conclusions, damage index levels for the following categories were established and are contained in the report: plaster on wood lath, plaster on metal lathe, plaster on concrete block, plaster on gypsum lathe, new gypsum board, and nail popping in new gypsum board.

The Oklahoma City sonic boom tests (see capsule summary SR-12), while just as extensive as those of the present investigation, had a different purpose. The purpose of those tests was to determine the rate of normal deterioration as compared to the rate of deterioration found during the 26-week sonic boom period, while the purpose of the present investigation was to determine sonic boom overpressure, damage index levels associated with various types of structural materials. As a result, the overpressures to which the buildings were subjected in the present investigation were much higher than those of the Oklahoma City sonic boom tests. Thus the results of these two investigations, which, along with the Edwards Air Force Base sonic boom experiments (see capsule summary SR-39), are the most extensive that have been conducted concerning structural response to sonic booms, complement each other.

SR-17
STRUCTURAL REACTION PROGRAM NATIONAL SONIC BOOM STUDY PROJECT
John A. Blume & Associates Research Div., San Francisco, Calif., SST Dev. F.A.A., Report No. SST-65-15, Vol. 2, April 1965

The first volume of this report (see capsule summary SR-16) presents the results of a study of the effects of sonic boom at varying levels of overpressure on selected structures and materials conducted at the White Sands Missile Range, New Mexico from November 18, 1964 through February 15, 1965. This volume contains the appendices to Volume 1. Contents include background material, test structures, instrumentation, and loading and response data.

SR-18
STUDIES OF SONIC BOOM INDUCED DAMAGE
Clark, Buhr & Nexsen
NASA CR-227, May 1965

The results of a study involving supersonic flights over St. Louis, Missouri during the periods of November 6 through 12, 1961 and January 3 through 6, 1962 are presented in this report. The phase of the over-all test program that is covered by this report constitutes research of typical sonic boom claims, investigation of alleged damage to structures caused by the specific test flights, and compilation and organization of field data into a comprehensive report. During the two test periods a total of seventeen supersonic flights were accomplished in a predesignated flight corridor by a B-58 bomber and an F-106 fighter.

The following conclusions were reached as a result of this investigation:

1. Sonic boom overpressures (0.3 - 2.6 psf) generated by aircraft operating at the speed (between M=1.5 and M=2.0) and altitude (31,000 - 41,000 feet) used for the test flights were not of sufficient magnitude to cause structural damage to well constructed and well maintained buildings. Building components such as glass, plaster, etc., that tend to develop concentrations of internal stress are subject to limited damage caused by sonic boom triggering cracking of stressed areas.

2. Poorly constructed and poorly maintained structures and structures experiencing deterioration due to age are subject to greater amounts of damage.

3. Complaints of plaster and glass damage occurred most frequently both during the test flights and in cases on file in Air Force centers handling complaints.

4. Sonic boom damage complaints can be expected to be more numerous closer to the aircraft flight track and to diminish with increase of distance from the track. This will hold true if the population density is approximately evenly distributed, and the condition of the buildings approximately the same.

5. The test flight results indicated that about 90 percent of all complaints in the greater St. Louis area occurred within a corridor of twelve miles on each side of the aircraft flight track.

6. The manner in which the area residents have been acquainted with sonic boom causation, its capability to induce damage, and the responsibility therefor will have a bearing on the number of complaints and claims to be expected.

The later sonic boom studies conducted in Oklahoma City and White Sands, New Mexico (see capsule summary SR-12 and SR-16, respectively) were much more extensive than the present investigation. Furthermore, while the present investigation was concerned only with damage reported by the populace of St. Louis during the tests, the later studies obtained data as to the actual structural response of various structural components of buildings to varying overpressures by extensive instrumentation of test structures. However, the conclusions of the present investigation do agree with the conclusions reached in the corresponding subject areas of the later investigations.

SR-19
A STUDY OF METHODS FOR EVALUATING SONIC BOOM EFFECTS
J. D. Revell, J. R. Thompson
Lockheed-California Company, Report No. 18996, July 1, 1965

Two methods for predicting and evaluating the effects of sonic booms on people and structures are compared in this report. One method utilizes digital techniques to compute the variation with frequency of the power spectral density of the signature and yields results in agreement with analytical Fourier transform solutions for N-waves. The other utilizes conventional transient time-history techniques to compute the maximum dynamic deflection response of a single-degree-of-freedom oscillator to the pressure signature.

The characteristics of sonic boom effects as predicted by the two methods are shown to be similar except for the effect of period length. The spectrum method indicates that increase in period reduces power at frequencies above the fundamental, whereas the transient method indicates that increase in period increases the response at frequencies above the fundamental. The transient analysis is considered to give the theoretically correct result.

It is concluded that the transient time-history method is the more reliable of the two methods presented. The spectrum method appeared to provide valid comparisons of signature variables other than length, however, and was more convenient to use.

This is a good comparison of the two primary methods of predicting sonic boom effects of [illegible] structures.

SR-20
EFFECT OF SONIC BOOMS OF VARYING OVERPRESSURES ON SNOW AVALANCHES
D. C. Lillard, T. L. Parrott, D. C. Gallagher
F.A.A. Report No. SST 65-9, August 1965

This report presents the results of a sonic boom study conducted during the period March 18-20, 1965 in the Star Mountain area near Leadville, Colorado, in the San Isabel National Forest. The purpose of this study was to determine the effects of sonic boom overpressures on snow avalanches. A total of 18 combined F-104 and F-100 runs were made with measured overpressures ranging from 1.5 to 5.2.

Two avalanches were observed in the general area of the target during the test. One was caused by a high explosive projectile. The cause of release of the other one was unknown. No avalanche was observed as a direct effect of the sonic booms. Forest Service personnel rated the avalanche hazard as "low" during the test period, resulting in a recommendation for further tests during periods of "high" avalanche hazard.

This is the only flight test investigation that has been conducted to determine the effect of sonic booms on snow avalanches.

SR-21
THE EFFECTS OF SONIC BOOM ON STRUCTURAL BEHAVIOR
A SUPPLEMENTARY ANALYSIS REPORT
John H. Wiggins, Jr., Federal Aviation Agency
SST Report No. 65-18, October 1965

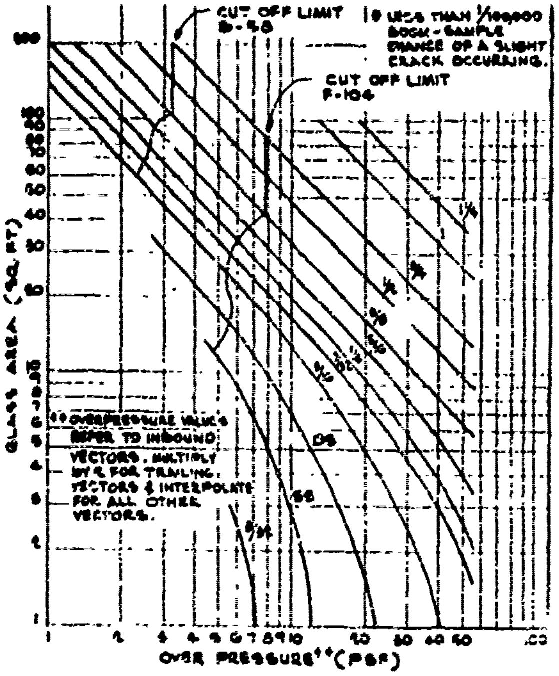
Response and damage data from the Federal Aviation Agency Sonic Boom Tests at Oklahoma City, Oklahoma, and White Sands, New Mexico, are analyzed and effects on structures summarized in this report. This report was designed to supplement previously published reports (see capsule summaries SR-12, SR-13, SR-16, SR-17, P-42, and P-15), and to be used together with them. It summarizes the findings in the Oklahoma City and White Sands reports and incorporates the pertinent work and findings done by other investigators in the general area of sonic boom.

Parameters governing the free-field and near-field boom waves are studied and their influence on scatter in the data estimated statistically. The results are then conservatively summarized in the damage prediction table and chart shown below. Insurance adjusters are given guidance on the treatment of sonic boom damage claims along with the chart.

Material	White Sands Mean[2]	Max[3]
Interior Walls and Ceilings		
1. plaster on wood lath	2.3	4.6
2. plaster on gypsum lath	7.5	14.
3. plaster on expanding metal lath	10.	19.
4. plaster on concrete block	10	16.
5. gypsum board (new)	10	16.
6. gypsum board (old)	4.5	16.
7. [illegible] (new)	2.6	16.
8. bathroom tile (old)	4.8	8.5
9. damaged suspended ceiling (new)	4.0	16
10. stucco (new)	3.5	16
Bric-a-brac		
1. extremely precariously placed or unstable items	NA[4]	3.1
2. normally stable or placed items	NA	6.6
Miscellaneous		
1. [illegible] cracked	10	..
2. [illegible]	10	..
3. [illegible]	9	..
4. [illegible] molding	10	..

1. Low [illegible] chance in 10,000 when within five miles of flight track. This value corresponds to a [illegible] 99 percent confidence that damage will not occur.
2. Small (less than three inches) [illegible] or pre-damaged paint chipping or spalling.
3. Peeling plaster or tile etc.
4. Not applicable.

Maximum safe[1] predicted or recorded peak overpressure for representative building materials and bric-a-brac other than glass



Maximum safe predicted or measured average ground overpressure for plate and window glass*

The following are some of the conclusions reached as a result of this study:

1. Secondary pulses in a boom wave generated by aircraft design features modify both free-field and loading (dynamic amplification factor) spectra. F-104 booms amplify the second harmonic about 14 percent more than predicted by a theoretical N-wave spectra. The first harmonic is amplified somewhat less than the theoretical value of 2.3.

2. Dynamic amplification factor (DAF-defined as the ratio of equivalent static load to peak dynamic load) spectra computed from records taken on a wall differ from free-field spectra and depend on the aircraft vector with respect to the wall surface. Inbound vector booms lower the first harmonic DAF and raise the second. Trailing vector booms cause the opposite to occur.

3. Stiffness of a wall does not change the DAF spectrum of the loading wave markedly.

4. Peak boom pressures can be increased in a predictable manner when the boom wave travels into a corner.

5. DAF increases with height above ground. The rate of increase depends directly on the N-wave duration. Since peak pressure decreases with height, effective load should no more than equal load on near-ground, (one story) structures.

6. The net load on a window (outside minus inside) differs from the outside load. The effective static load is lower than that computed from the outside load only.

7. B-58 booms, when normalized to peak pressure, cause lower response of wall and ceiling elements than smaller F-106 or F-104 aircraft in 4 out of 5 tests of sample data taken at Oklahoma City and White Sands.

8. Inbound vector booms can stress windows up to four times as much as trailing vector booms.

9. Inbound vector booms can displace walls in the diaphragm mode more than twice as much as trailing vector booms.

10. Glass breakage is caused primarily by impact against stress raisers.

In a later paper (see capsule summary SR-35) Wiggins again summarizes and analyzes the finding of the Oklahoma City and White Sands sonic boom tests. The two summaries, although similar, each treat certain subjects not covered in the other. Both are excellent summaries of two very important sonic boom tests.

SR-22
RESULTS OF USAF-NASA-FAA FLIGHT TEST PRO ..M TO STUDY COMMUNITY RESPONSE TO SONIC BOOM I" THE ST. LOUIS AREA
Charles W. Nixon and Harvey H. Hubbard
NASA TN D-2705, 1965

In this report data are presented from a series of community reaction flight-test experiments in which the population of St. Louis, Missouri was repeatedly exposed to sonic booms in the range of overpressures up to about 3.1 psf. Results include those obtained from direct interviews, analyses of complaint files, and engineering evaluations of reported damage. These results are correlated with information on aircraft operations and sonic boom pressure measurements. Only the results concerning structural response will be summarized here. For a discussion of the results concerning human response the reader is referred to capsule summary HRSC-15.

There were some carefully monitored special flights during the test period as well as several unmonitored flights previous to the test period. The first flight was made in July 1961, and up to the time of the community response study at least 34 flights were known to have been made. Thirteen special flights of B-58 and F-106 aircraft were made in a selected cor idor which passed along the edge of the main urban area of greater St. Louis at various times of day and night during a six-day period beginn..g November 7. Subsequent to these special flights, 29 others were known to have been made. Four of these, which occurred on January 3, 1962 and January 6, 1962 were also special flights at a relatively lower altitude and with higher associated sonic boom pressures. A total of 76 supersonic flights was thus known to have been made in the est area during a 7-month period.

During the special series of 16 flights, a special effort was made to evaluate the damage reported in complaints related to these flights. The Scott Air Force Base office personnel who were on duty at appropriate times to receive telephone complaints worked closely with investigating teams made up of U. S. Air Force and the contractor's investigating personnel who, whenever possible, made prompt on-the-spot investigations at all sites from which complaints originated. In most cases these investigations were accomplished within a few hours of the time of the flight. The objectives of such prompt investigation were to evaluate the reported damage, to determine the nature of it, and to establish its validity.

The final total number of claims arising out of this time period of operations in the greater St. Louis area was determined from USAF files to be 1,624 as of January 1964. Several hundred additional claims came in during the ensuing time period of about 1-1/2 years. The total value of all claims registered was $366,019.03. Of this number, 825 claims were approved for a total of $58,648.23 or an average of about $71 each.

The following conclusions were reached as a result of this investigation:

1. Reported building damage was superficial in nature, plaster and glass cracks being most numerous. Engineering evaluations showed that there were contributing factors other than sonic booms in many cases and that a large portion of reported damage incidents were probably not valid.

2. Approximately 20 percent of the recorded complaints ultimately resulted in formal claims for compensation.

3. For the range of overpressures 0.4 to 2.3 lb/sq.ft., a maximum of 0.87 "valid" damage incidents per flight per million population were tabulated.

The structural response results of the St. Louis sonic boom tests are also discussed in the report summarized in capsule summary SR-18.

This was the first community response flight test program conducted. The later sonic boom studies conducted in Oklahoma City and White Sands, New Mexico (see capsule summaries SR-12 and SR-16, respectively) were much more extensive than the present investigation.

SR-23
AN INVESTIGATION OF GROUND SHOCK EFFECTS DUE TO RAYLEIGH WAVES GENERATED BY SONIC BOOMS
M. L. Baron, H. H. Bleich, J. P. Wright
NASA CR-451, May 1966

This report considers the amplification of shock effects on surface structures for the case of an elastic solid when the velocity of the traveling pressure wave is equal to, or close to, the velocity of Rayleigh waves in the medium. The analytical problem studied is the effect of a traveling crescent shaped pressure distribution at points at or near the surface of an elastic semi-infinite medium over which the wave moves.

Expressions are derived for the steady state vertical displacements produced at the surface of an elastic half-space by a line load of finite length which moves with a constant velocity in a direction either parallel or perpendicular to its length. These expressions are used to estimate the response of structures to the seismic disturbances produced by a sonic boom which moves at speeds close to the speed of surface waves in the medium. Shock amplification factors for the accelerations imparted to the structure are obtained for a range of parameters. The results show that the accelerations produced at these speeds are generally quite small, and that the resonance peak which occurs when the applied load moves with the surface wave speed is extremely narrow. Thus the authors do not recommend continuation of analytical work on sonic boom effects transmitted to structures by surface waves in the ground.

Seismic effects of sonic booms are also investigated in the papers summarized in capsule summaries SR-49 and SR-50.

SR-24

DEFINITION STUDY OF THE EFFECTS OF BOOMS FROM THE SST ON STRUCTURES, PEOPLE, AND ANIMALS

K. D. Kryter & Staff (Definition Study Group)
Stanford Research Institute, Technical Report 1, June 1966

This report presents a brief study of the problems related to the effects upon structures, people, and animals of sonic booms from overland flights of a commercial supersonic transport and defines further research studies that might be required to resolve such problems. A summary of previous results, including those obtained in the Oklahoma City and White Sands, New Mexico sonic boom tests (see capsule summaries SR-12 and SR-16, respectively), is given.

The Definition Study Group concluded that the following five research studies should be undertaken in order to provide answers as scientifically sound and complete as possible:

Study I - Community Reaction Study

Study II - Edwards Air Force Base Sonic Boom Experiment

Study III - Analysis of Potential Costs of Structural Damage due to SST Operations

Study IV - Study of the Response of Animals to Sonic Booms

Study V - Experiments on the Audibility of Sonic Booms and Their Effects on Sleep and Startle

Study II, Study IV, and Study V were later carried out as recommended (see capsule summaries SR-39, AR-2, HRSC-40, and HRSC-53, respectively).

SR-25

REPORT ON DATA RETRIEVAL AND ANALYSIS OF USAF SONIC BOOM CLAIMS FILES

C. A. Grubb, J. E. VanZandt, C. Curione, and C. A. Kamradt
Stanford Research Institute, Interim Technical Report 2, July 1966

The purpose of this supplementary study was to retrieve certain data from the USAF sonic boom damage files, the only known complete source of information on sonic boom damage to structures in four major U. S. cities -- Chicago, Pittsburgh, Milwaukee, and Oklahoma City. One goal was to obtain information leading to definitions of damage under "plate" and "racking" modes, as this information was believed to be a significant parameter in the analysis of structural response to sonic booms, particularly to the correlations between various types of damage and certain types of aircraft flying at supersonic speeds. A review and analysis of sonic boom damage trends, characteristics, and relationships to specific structural types was considered equally important.

The results of this evaluation are shown in an extensive series of charts, graphs, and curves. The following are some of the conclusions reached:

1. Although the ratios of "total claims to complaints" and "paid claims to adjudications" fell in a relatively consistent pattern, the latter ratio was much lower for Oklahoma City than for the other three cities. Either the fighter aircraft used in the Oklahoma City tests did not cause a proportionate amount of valid damage compared with the B-58s in the other areas, or a more stringent payment policy was exercised in Oklahoma City.

2. Although 80 percent of the complaints were registered during the period of sonic booms, only 50 percent of the total number of claimants actually filed a formal claim during the same period.

3. The predominant failure mode for glass is plate. Racking accounts for less than one-third of the glass failures.

4. Plate was the predominant failure mode in all damaged surfaces except Pittsburgh where excessive falling plaster caused a reverse trend.

The results of the Oklahoma City tests and the Chicago tests are also discussed in the papers summarized in capsule summaries SR-12 and SR-29, respectively. The present paper is the only one available which discusses sonic boom damage claims data for Pittsburgh and Milwaukee.

SR-26

GROUND MEASUREMENTS OF SHOCK-WAVE PRESSURE FOR FIGHTER AIRPLANES FLYING AT VERY LOW ALTITUDES AND COMMENTS ON ASSOCIATED RESPONSE PHENOMENA

D. J. Maglieri, V. Huckel, T. L. Parrott
NASA TN D-3443, July 1966

This paper presents the results of extensive ground measurements of sonic boom intensities for two fighter airplanes in the Mach number range of about 1.05 to 1.16 and for altitudes from about 50 to 890 feet. Comparisons of the pressure rises across the shock wave measured on the ground are made with the available theoretial data. These pressure data are correlated with some data on glass window breakage, and brief discussions are also given relative to other associated phenomena such as ground motions and response of equipment and personnel.

The experimental setups were located on a dry lake bed on the Las Vegas Bombing and Gunnery Range, which is about 50 miles north of Las Vegas, Nevada at an altitude of 3,000 feet. Window-glass models of each of two different window styles were attached to plywood and frame cubicles and positioned in the test area to study glass-breakage phenomena. The plain windows contained glass approximately 1/8 of an in. thick and approximately 11 in. square. The colonial windows incorporated 9 panes of glass, each of which was approximately 3/32 of an inch thick and approximately 11 in. square. Standard wooden frames and mullions were used. The cubicles to which the windows were attached had volumes ranging from approximately 16 cubic feet to 96 cubic feet.

The results of the window-breakage experiments indicated that of the 214 tests of windows,

51 breakages actually occurred within the pressure range of about 20 to 100 pounds per square foot experienced during the tests. As might be expected, a higher percentage of failures generally occurred with increased peak pressure rise across the shock wave. It was also found that the detailed characteristics of the pressure time histories are significant. More damage occurred for the time histories having longer time durations of the first positive pressure rise across the shock wave. When glass failure occurred, the fragments were noted to come to rest at the base of the window and in close proximity to it.

The overpressure levels involved in these tests were much larger than those of any other similar tests that have been conducted. Thus the results for these high levels of overpressure complement those of other studies, such as the White Sands, New Mexico sonic boom tests (see capsule summary SR-16).

SR-27

THEORETICAL STUDY OF STRUCTURAL RESPONSE TO NEAR-FIELD AND FAR-FIELD SONIC BOOMS

J. H. Wiggins, Jr. and Bruce Kennedy

Datacraft, Inc., Final Report, Contract No. AF 49 (638)-1777, October 1966

This study investigates the difference in structural response between that due to near-field and that due to far-field sonic boom pressure signatures. To do so, it defines a new intensity standard, effective static load which depends on load waveform as well as magnitude. Many sonic boom loading waveforms are computed for 19 structural elements of various types produced by two SST designs as well as F-104, B-58, and XB-70 aircraft.

The following conclusions were reached:

1. Near-field intensities in general are lower than far-field intensities. They are lower than those predicted by the peak overpressure criterion. Several factors combine to produce the differences.

   a. near-field, free-field overpressures are lower than those predicted by the far-field theory,

   b. the near-field loading waves have lower maximum loads than the far-field waves, and

   c. the dynamic amplification factors are slightly lower.

   In general, the larger the variation in waveform appearance between near- and far-field theory, the lower the near-field intensity.

2. No significant differences of coefficient of variation between near- and far-field intensities were noted.

3. Racking intensities decrease slightly with increasing size and speed of airplane.

4. Plate intensities increase slightly with increasing size and speed of airplane.

This was the first investigation to specifically consider the difference between structural response to near-field sonic booms and structural response to far-field sonic booms.

SR-28

TRANSIENT RESPONSE OF STRUCTURAL ELEMENTS TO TRAVELING PRESSURE WAVES OF ARBITRARY SHAPE

D. H. Cheng and J. E. Benveniste

International Journal of Mechanical Sciences, Vol. 8, 1966, pp. 607-618

A method for studying the dynamic response of simple structural elements exposed to traveling pressure waves having arbitrary wave shapes is presented. The transient responses of simple beams subjected to a uniformly distributed pulse and to a point load moving across the span at a constant speed is obtained using Fourier sine transforms. This is followed by an analogous case of simple plates subjected to a uniformly distributed pulse and a moving line load. For pressure waves of arbitrary shape, the structural response is obtained by a simple superposition. The study is limited to the case in which the shock wave is traveling at the resonant velocity of the structural element, defined as $v = w_n a/m\pi$,

where w = angular frequency

a = panel length in x-direction (direction of largest dimension)

and m = mode number in x-direction.

As an illustrative example, an N-shaped pressure wave is used to evaluate the responses of beams and plates. It is found that for small period ratio (duration of pressure wave to fundamental period of structure), the maximum dynamic amplification always occurs after the wave has left the span. Furthermore, the greatest dynamic effect occurs when the wave travels in the direction of the deflection of the structural element. (The authors define the amplification factor, when maximum stress is the quantity of most interest, as the ratio of dynamic to static center moments, the static moment being caused by a uniformly distributed peak pressure over the entire structure.)

In a later paper (see capsule summary SR-40) Benveniste and Cheng extend the analysis of the present paper to the case of an N-wave acting on a beam whose end supports are pairs of springs having a gap within which the beam may freely move. It is found that the effect of sonic boom on a beam that rattles is much more severe than on one that does not.

SR-29
SONIC BOOM MEASUREMENTS DURING BOMBER TRAINING OPERATIONS IN THE CHICAGO AREA
David A. Hilton, Vera Huckel, and Domenic J. Maglieri
NASA TN D-3655, 1966

Bomber training operations were conducted by the Air Force in Chicago, Illinois from January 4 to March 31, 1965. This paper analyzes the measured sonic booms resulting from these flights in order to evaluate the effects of the atmosphere. A summary of this analysis is presented in capsule summary P-62. The discussion here concerns a table presented in the appendix of this report showing the sonic boom damage complaints and claims received as a result of these flights. This table is shown below.

Category	Number of complaints received	Number of claims received	Number of claims approved	Payments approved
Glass	3,383	1,788	1,150	$ 92,982
Plaster	2,654	623	153	16,000
Damage to structures	85	106*	15	1,517
Personal injury	18	1	0	0
Miscellaneous	976	387	114	3,754
TOTAL	7,116	2,964	1,442	$114,763

*These claims were originally classified as plaster damage, however, upon investigation they were reclassified as structural damage

Damage complaints and claims received

It can be seen from the table that by far the largest number of claims and approved claims were for glass damage. No claims were approved for personal injury and only 15 were approved for damage to structures. Thus for sonic boom levels in the order of those experienced as a result of these flights (~ 2 psf), the bulk of the sonic boom claims can be expected to be for glass damage.

S-·':
ACOUSTICAL AND VIBRATIONAL STUDIES RELATING TO AN OCCURRENCE OF SONIC BOOM INDUCED DAMAGE TO A WINDOW GLASS IN A STORE FRONT
Richard L. Lowery and Don K. Andrews
NASA CR-66170, 1966.

Mathematical models are formulated and applied in this paper to a specific incident of damage to a window glass in a store front which occurred during the series of sonic boom test flights at Oklahoma City in 1964. In this incident an 8' x 10' x 1/4" plate glass window in the store front of a single-story commercial building was broken coincidentally with the occurrence of a sonic boom. Using this specific incident of glass breakage as an example, an analysis was made of vibrational and acoustic factors which may have been involved to determine if any of these factors could have contributed to the failure of this particular window from this particular sonic boom. In a concurrent and related study (see capsule summary SR-32) a mathematical model was developed to calculate the pressure-time history acting on the glass window to determine if a shock wave with a pressure signature such as the one measured approximately 5 miles from the window in question could have been altered significantly by building orientation and configuration. This related study indicated that, theoretically, no abnormal or unusual pressure-time condition would have been produced.

Hence the approach taken for this study was as follows:

1. Determine all significant physical characteristics and dimensions of the building.

2. Formulate mathematical models of the building taking into account as many factors as possible that could influence the dynamic response of the window. These factors include the acoustical coupling between the ceiling and windows as well as the acoustical coupling with other rooms within the building.

3. Determine the stress to which the mathematical models were subjected in response to an assumed sonic boom.

4. Study the possibility of failure, taking into account the statistical strength of glass in response to the assumed sonic boom.

Formulation of the models was based upon measured and calculated data. The natural frequencies of the ceiling and window were measured with appropriate instruments and the existence of coupling between the ceiling and windows was verified by steady-state vibration tests. The masses of the various elements were calculated after physical dimensions had been tabulated. The elastic properties were calculated from the known natural frequencies and calculated masses.

The response of the lumped parameter system was obtained by two means: (1) the analogue computer, and (2) the digital computer. The analogue computer was used to study specific cases whereas the digital computer was used to solve for maximax values as a function of several parameters.

The following conclusions were reached as a result of this study:

1. Acoustic coupling exists between the ceiling-roof structure and the windows of the store building but cannot be considered of consequence for this particular case.

2. The stress level of the window in question which would have been produced by the assumed 1.65 psf and .135 second duration sonic boom could not cause failure of a properly installed, undamaged window glass.

3. The natural frequency of the ceiling-roof structure changes with time and appears attributable to changes in wood moisture content.

4. There are no openings of sufficient size to be classified as necks of Helmholtz resonators in this system.

5. The boundary conditions of the windows as mounted in the aluminum mullions can be considered to be simply supported.

The breakage of this window was also investigated by Zumwalt (see capsule summary SR-32).

This is a good example of the application of sonic boom structural response theory to a specific damage incident.

SR-31
ENERGY SPECTRAL DENSITY OF THE SONIC BOOM
J. R. Young
Journal of the Acoustical Society of America, Vol. 40, No. 2, 1966, pp. 496-498

This brief note presents equations for calculating the energy spectral density of ideal sonic-boom pressure signatures and the asymptotic behavior of the spectra at high and low frequencies. It is shown that, for systems with essentially high-frequency response characteristics, the system will be basically sensitive to peak overpressure and not to N-wave duration. Low-frequency systems are shown to be sensitive to both duration and peak overpressure. Experimental data from the White Sands, New Mexico sonic boom tests (see capsule summary SR-16) are cited to corroborate these conclusions.

This is a significant paper in spite of its brevity in that it was the first to show that high frequency systems respond to peak overpressure and low frequency systems respond to both peak overpressure and N-wave duration.

SR-32
COMPUTATION OF THE PRESSURE-TIME HISTORY OF A SONIC BOOM SHOCK WAVE ACTING ON A WINDOW GLASS IN A BUILDING
Glen W. Zumwalt
NASA CR-66109, 1966

In this paper mathematical methods are presented for computing the pressure-time history of a sonic boom shock wave acting on any given exterior wall surface facing the shock wave. Additional methods are also presented for walls which are in the "shadow" of the shock wave or which receive reflected wave effects from nearby walls or corners.

Three methods are presented for calculating the time-of-passage of an incident wave and the time interval between incident and reflected waves for a wall facing the wave. Method I used a conical wave analysis which treated the speed of sound as constant and equal to that of ground level and which assumed that no wind effects were present. Method II used a more exact ballistic wave analysis based on the theory developed by Lansing (see capsule summary P-24). In this method the speed of sound was assumed to vary linearly up to the tropopause and to be constant at 972 ft/sec above the tropopause. It was again assumed that there were no winds. Method III attempted to reduce the computer time required by Method II without sacrificing too much accuracy. The simplifying assumption added was that $\frac{dY}{dZ}$ of the ray was constant at the value of the flight altitude (y is horizontal coordinate axis perpendicular to flight path and z is vertical coordinate axis), while the linear variation of speed of sound below the tropopause was retained.

It was found that the three methods gave almost identical results for small offset distances from the flight track (10,000 feet or less). The differences in results were greatest at low Mach numbers and large offset distances (up to 70,000 feet). The conical wave analysis (Method I) gave the poorest accuracy. Method III was found to be the most practical method.

An analysis of N-wave diffraction and reflection around structures was then made. The two-dimensional theory of Keller and Blank (Keller, J. B. and Blank, A., "Diffraction and Reflection of Pulses by Wedges and Corners," Communications on Pure and Applied Mathematics, Ser. 4, No. 1, June 1951) was adapted to produce a series of pressure perturbation expressions for multiple wave reflections.

The methods developed are then applied to a specific window location of a building wall at which it is believed the window glass was broken by a specific sonic boom from one test flight during the series of 1,253 sonic boom test flights at Oklahoma City in 1964.

The calculated pressure-time history acting on this window glass location, from this particular sonic boom, indicated that no abnormal or unusual pressure-time condition would have been produced. However, it is stated that these calculations were based on several assumed atmospheric conditions and flight data values of which some were of doubtful validity. It is concluded that development of confidence in these or other analytical methods and the determination of the validity of various assumptions as to both atmospheric conditions and flight test data values will require specific field tests designed and conducted for this purpose.

The breakage of the store-front window in the Oklahoma City tests was also investigated by Lowery and Andrews (see capsule summary SR-30). No definite cause for the window failure was found in that investigation either.

SR-33
DYNAMIC EFFECTS OF SONIC BOOMS ON A BEAM LOOSELY BOUND TO ITS SUPPORTS
J. E. Benveniste and D. H. Cheng
AIAA Paper No. 67-14, Presented at AIAA 5th Aerospace Sciences Meeting, New York, New York, January 23-26, 1967

This paper is exactly the same as the one discussed in capsule summary SR-40. The reader is referred to that capsule summary for details of this work.

SR-34
RESPONSE OF WINDOWS TO SONIC BOOMS
L. Seaman
Stanford Research Institute, Interim Technical Report No. 7, June 1967

This report presents a method for calculating the response of simply supported windows to sonic booms. The procedure is based on a linear one-degree-of-freedom analysis plus estimates of the importance of nonlinear and multimodal effects. Effects of stress raisers and of movement followed by impact of loose windows are not considered. It is shown that significant contributions to the maximum stress in windows subjected to 2 psf sonic booms are made by large deflections (nonlinearities), modes above the fundamental, and the internal pressure built up in the building by the boom. An attempt to estimate statistically the occurrence of window failure due to 2 psf booms was frustrated by lack of sufficient knowledge of the statistical distribution of glass strength.

SR-35
EFFECT OF SONIC BOOM ON STRUCTURAL BEHAVIOR
J. H. Wiggins, Jr.
Materials Research and Standards, June 1967, pp. 235-245

A summary of the findings of the Oklahoma City and White Sands Missile Range sonic boom tests (see capsule summaries SR-12 and SR-16, respectively) is presented in this paper. The following topics are discussed: (1) parameters affecting free-field and loading boom waves; (2) parameters influencing cracking damage; (3) factors influencing crack observation data; (4) analysis of crack data for cumulative damage; (5) identification and description of boom damage; and (6) forecasting boom damage.

The following conclusions were reached:

1. Boom-caused crack extensions at overpressures generated during the White Sands program were found to be few in number and hairline in size, and could be detected only on very close examination. This resulted from the fact that virtually no permanent distortion of the building frames was caused by F-104 booms of overpressures up to 24 psf.

2. Boom-caused cracking is below the "noise" level of cracking generated by natural causes as determined by subjective observation.

3. Structures and structural materials used in the White Sands tests appear to crack more rapidly during boom and non-boom time intervals at a mean free-field overpressure of about 10 psf generated by an F-104.

4. Glass breakage observed originated from edges and is caused primarily by impact against stress raisers.

5. There is no evidence of damage or cumulative damage occurring in the Oklahoma City test structures subjected to nominal overpressures equal to or less than 2.0 psf.

6. Boom damage can only be analyzed and predicted by first defining it (plaster crack, glass crack, etc.) and then treating it as a random variable with a certain standard deviation. Damage variability is governed by free-field, loading, and response variability as well as the inherent variation of common finishing material properties.

7. The direction of boom wave propagation in relation to the orientation of a structure or window therein is very important to its reaction. Booms traveling directly into a window cause the window to react more violently than do booms traveling away from the window.

Wiggins also wrote an earlier summary of the Oklahoma City and White Sands sonic boom tests (see capsule summary SR-21). The two summaries, although similar, each treat certain subjects not covered in the other. Both are excellent summaries of two very important sonic boom tests.

SR-36
RESPONSE OF STRUCTURES TO SONIC BOOMS
J. A. Blume, R. L. Sharpe, J. Proulx, and E. C. Kost
Sonic Boom Experiments at Edwards Air Force Base, Interim Report, NSBEO-1-67, July 28, 1967, Annex G, Part I, pp. G-I-1 thru G-I-3-5

This is a preliminary version of the report described in capsule summary SR-39. The reader is referred to that capsule summary for details of this work.

SR-37
VIBRATION RESPONSE OF TEST STRUCTURES NOS. 1 AND 2 DURING PHASE I OF THE SONIC BOOM EXPERIMENTS AT EDWARDS AIR FORCE BASE
D. S. Findley, V. Huckel, H. Hubbard, and H. Henderson
Sonic Boom Experiments at Edwards Air Force Base, Interim Report, NSBEO-1-67, July 28, 1967, Annex G, Part II, pp. G-II-1 thru G-II-42

The purpose of this paper is to present in brief summary form the measurements made in a one-story residence structure (Edwards test structure No. 1) and a two-story residence structure Edwards test structure No. 2) during the Edwards Air Force Base sonic boom experiments.

Included are sample acceleration and strain recordings from F-104, B-58, and XB-70 sonic boom exposures, along with tabulations of the maximum acceleration and strain values measured for each one of about 140 flight tests. These data are compared with similar measurements for engine noise exposures of the building during simulated landing approaches of KC-135 aircraft. Description of the test conditions, aircraft, aircraft positioning, weather observations, test structures, and instrumentation are presented in Annex A.

The following conclusions were reached as a result of these measurements:

1. The sonic boom induced vibration responses were generally less than one second in duration and contained frequencies associated with both primary and secondary structural components.

2. Wall acceleration amplitudes increased generally as a function of the sonic boom overpressure, and the F-104 seemed to induce the largest amplitudes for a given overpressure.

3. Strains in a large window increased generally as overpressure increased with no particular trend as a function of airplane size. Considerable variation in peak response amplitudes was noted for the same nominal flight conditions.

The fact that the wall acceleration amplitudes were larger for the F-104 than for the B-58 and XB-70 at a given overpressure combined with the conclusions reached by Young (see capsule summary SR-31) that high frequency systems respond to peak overpressure and low frequency systems respond to both peak overpressure and duration indicates that the walls of the test structures were high frequency systems.

SR-38
GROUND SHOCK DUE TO RAYLEIGH WAVES FROM SONIC BOOMS
M. L. Baron, H. H. Bleich, J. P. Wright
Journal of the Engineering Mechanics Division, Proceedings of the American Society of Civil Engineers, EM 5, October 1967, pp. 137-162

This paper is identical to an earlier NASA Contractor Report summarized in capsule summary SR-23. The reader is referred to that capsule summary for details of this work.

SR-39
RESPONSE OF STRUCTURES TO SONIC BOOMS PRODUCED BY XB-70, B-58 AND F-104 AIRCRAFT
J. A. Blume, R. L. Sharpe, G. Kost, J. Proulx
Final Report to National Sonic Boom Evaluation Office, NSBEO-2-67, October 1967

This report summarizes the work performed by John A. Blume & Associates Research Division during the sonic boom experiments at Edwards Air Force Base. A detailed discussion of findings derived from analyses of the data measured and recorded is presented.

The general objective of the structural response portion of the Edwards Air Force Base Program was to determine the response of typical structures to sonic booms having different signature characteristics and evaluate damage resulting from the program overflights. The response of test structures and structure elements to sonic booms produced by XB-70, B-58, and F-104 aircraft was studied. These aircraft were flown at several flight track offsets, altitudes and Mach numbers so as to generate different overpressure levels and signature characteristics.

The findings presented in this report are based on detailed analyses of structural response and free-field overpressure data for seventeen comparable XB-70, B-58, and F-104 missions flown within minutes of each other. The measured plate response of three gypsum board/wood stud/wood siding walls and one large plate glass window, and the measured racking response of two typical wood frame houses, one one-story and one two-story house, were analyzed in detail and compared with the response predicted using boom signatures. In addition, the plate and racking response of a long-span steel frame-metal siding building was analyzed.

Free-field signature data and the effects of free-field signature parameters on structural response were analyzed and the following are the major findings:

1. Sonic booms from large aircraft such as the XB-70 affect a greater range of structural elements (those elements with natural frequencies below 5 cps) than sonic booms from smaller aircraft such as the B-58 and F-104. These results are predictable if the boom and structure element characteristics are known. The natural frequency at which the maximum DAF (Dynamic Amplification Factor-defined as the ratio of equivalent static load to peak dynamic load) occurred was primarily a function of the time from start of boom to negative peak T_2. As T_2 increased, the maximum DAF occurred at a lower natural frequency. T_2 increased as size of aircraft increased.

2. The DAF computed from free field signatures and peak positive free-field overpressures were independent of the channel on which the signatures were recorded. Therefore, a single free-field microphone would have supplied sufficient data to predict structural element response.

3. The ratio P_2/P_1 (absolute value of peak negative overpressure to peak positive overpressure) decreased as the offset of the aircraft increased for XB-70 missions. The magnitude of the maximum DAF decreased as the ratio P_2/P_1 decreased.

4. The DAF spectra obtained using a wave model described by free-field signature parameters P_1, P_2, T_1, and T_2, where T_1 is rise time, were equal at the 95 percent confidence level to the DAF spectra obtained from digitized free-field signatures. The wave model can be used to predict structure response if these parameters and the characteristics of the structure element are known.

5. In the analysis of the effects of lateral offset of aircraft, the ratio P_2/P_1 in the recorded free-field signatures caused the predominant effect on DAF. The recorded signatures showed little change in rise time (T_1) or in durations (τ) for overhead and offset missions for each type of aircraft. Therefore the influence of lateral offset on DAF spectra was limited to the effect of the ratio P_2/P_1.

The plate and racking response of the one-story and two-story test houses (E-1 and E-2, respectively) and of the long span steel frame structure (E-3) to sonic booms generated by the Edwards AFB test flights were analyzed. The major findings were as follows:

1. Peak plate displacements of three typical walls in the two test houses were less than 0.034 inches for sonic boom overpressures of approximately 2 psf. Racking displacements at the roof line of the northeast corners of Test Houses E-1 and E-2 were extremely small (less than 0.0018" for E-1 and less than 0.005" for E-2) for sonic booms on the order of 2 psf.

2. Measured displacements of three typical walls were nearly equal to predicted displacements based on either free-field or net pressure signature data. Racking displacements predicted from free-field peak overpressures and DAF spectra calculated from free-field pressure signatures were in good agreement with measured displacements. The response of the large glass window in E-1 was predictable using free-field signature data.

3. Structure response could be adequately predicted by using peak overpressures and DAF spectra calculated from free-field signatures.

4. Peak overpressures of about ? psf caused by a typical SST should pro[illegible] racking displacements of typical hous[illegible] that will be of similar magnitude, or p[illegible]ibly smaller, than those caused by the XB-70 missions. These racking displacements should be negligible and far less than those required to cause damage.

5. No sonic boom damage was observed in test structures prior to or after the test flights. There were minor shrinkage cracks in the test structures prior to start of test flights. However, no discernible extension or widening of these cracks was observed although observations were made and recorded daily.

6. Damage to properly designed and constructed houses from low magnitude sonic booms is extremely unlikely. Damage should not occur to structure elements such as glass windows from racking motions caused by low magnitude sonic booms.

The supersonic test missions subjected a large number of buildings and structures at Edwards AFB and in communities near Edwards to sonic booms. A survey was made of all glass windows and doors in buildings and structures at Edwards to provide a basis for determining the extent of glass damage caused by the test program. An engineering investigator inspected each complaint received from Edwards and adjacent communities. The major findings were as follows:

1. As the condition of the glass panes at Edwards AFB was determined prior to the test program, the number of damaged panes caused by booms from test missions should be an indicator of glass damage to be expected from future level supersonic flights generating peak overpressures of 2 to 3 psf. The rate was one damaged pane per 7.9 million boom-pane exposures. This rate was 27 percent of the rate for buildings in communities adjacent to Edwards which were not condition surveyed prior to test missions.

2. During Phase I, the 110,390 glass panes in structures at Edwards were subjected to more booms from test missions than were the 605,000 glass panes in the adjacent communities; however, the aircraft while over Edwards were flying straight courses and then made turns at supersonic speeds over adjacent communities. Some focusing of the boom overpressure (super booms) may therefore have been produced with peak overpressures greatly exceeding those produced on the Base. As a result, the valid glass damage rate per mission during Phase I was 8.8 times the rate during Phase II when aircraft generally flew straight courses while at supersonic speeds.

3. Fifty-eight percent of all incidents of damage for which complaints were received during Phases I and II were listed as possibly caused by sonic booms generated by test program flights. Of these valid incidents, 80 percent were for glass, 5.5 percent for plaster or stucco, 0.0 percent for structural, and 14.5 percent for bric-a-brac or other fallen object damage.

This experimental program, along with the one conducted at the White Sands Missile Range, New Mexico in 1964-[illegible] (see capsule summary SR-16) and the Oklahoma City sonic boom tests (see capsule summary SR-12), are the most extensive that have been conducted concerning effects of sonic booms on structures. The overpressures of the Edwards AFB experiments (on the order of 2 psf) were much lower than those of the White Sands tests (up to 38 psf. This was due to the fact that the purpose of the White Sands tests were to determine the overpressure levels required to damage various structural materials and components, while the purpose of the Edwards tests was to determine the response of typical structures to overpressure levels typical of SST cruise conditions. In this respect the Edwards AFB experiments were much more similar to the Oklahoma City tests.

SR-40

SONIC BOOM EFFECTS ON BEAMS LOOSELY BOUND TO THEIR SUPPORTS

J. E. Benveniste and D. H. Cheng

J. Aircraft, Vol. 4, No. 6, Nov.-Dec., 1967, pp. 494-498

The problem of a beam induced to rattle between two sets of springs by a sonic boom is formulated in this paper and a method of solution is presented. A detailed study is made of the dynamic response of the rattling beam subjected to an N-wave. The effect of damping is neglected. The response is expressed in either one of two normal function series, depending on whether or not the beam is in contact with its supports.

It is found that for moderately stiff springs, the dynamic amplification factors (ratio of dynamic to static center moments) are considerably higher for a beam that rattles than for a firmly supported beam. The dynamic amplification factor for shear increases very rapidly as the spring stiffness increases. For the particular case studied, an additional factor of 2 [illegible] indicated for the DAF on the moment at midspan and about 4 on the shear at supports. Based on this fact, it is suggested that a rattling beam would most likely fail near the supports instead of at the center, because the shear at supports which induces the diagonal tension and compression stresses would become more critical than the bending stress induced by the moment at the center of the beam.

Other factors included in the analysis are ratio of sonic boom duration to fundamental period of beam, ratio of gap to beam span, and ratio of static deflection to beam span. This last ratio affects the dynamic amplification factor, thus showing that the maximum response is not proportional to the peak pressure, making the problem nonlinear. It is concluded that the effect of a sonic boom on a beam that rattles is much more severe than on one that does not.

In a previous paper (see capsule summary SR-28) Benveniste and Cheng studied in detail the response of a simply supported beam to an N-wave (among other things). The present paper is an extension of that analysis.

SR-41
MULTIMODE RESPONSE OF PANELS TO NORMAL AND TO TRAVELING SONIC BOOMS
M. J. Crocker
Journal of the Acoustical Society of America, Vol. 42, No. 5, 1967, pp. 1070-1079

The general results for undamped panel response to an N-wave traveling across its surface at any arbitrary velocity are presented in this paper. A detailed theoretical study is made of the response of a uniform flat rectangular panel to an N-wave for both the case where the N-wave arrives normal to the panel surface and the case where the shock front arrives at any angle of incidence and crosses the panel parallel to one side. Closed-form solutions (for individual modes) are given for the case of simply supported panel response to normal and traveling N-waves, and an approximate solution is presented for the response of a panel with fully fixed edges to a normal N-wave. The Duhamel integral method is used to obtain panel displacement-, strain-, and stress-time histories for any point on the panel. The analyses derived can be used to compute window or wall-panel response to sonic boom.

A comparison between theory and experiment shows good agreement between measured and predicted strain maxima and fair agreement between the early parts of the strain-time histories, despite some differences between the experimental and theoretical models. The necessity to include the contributions due to the higher modes, particularly for accuracy in strain-time histories, is shown to be clearly borne out, both in theory and experiment.

Cheng and Benveniste (see capsule summary SR-28) performed a study similar to the one of the present paper. However, their results were restrict restricted to the so-called "resonant" velocity of shock propagation $v = w_m\, a/m\pi$,

where w = angular frequency
a = panel length in x-direction (direction of largest dimension)
and m = mode number in x-direction.

The present paper makes no such restriction, since the greatest deflection normally occurs for a velocity other than the resonant velocity.

SR-42
SONIC BOOM EFFECTS ON PEOPLE AND STRUCTURES
Harvey H. Hubbard and William H. Mayes
NASA SP-147, Sonic Boom Research, 1967, pp. 65-76

This paper presents a general discussion of experimentally determined effects of sonic booms on people and structures. Only the results concerning structural effects will be summarized here. For a discussion of the human response results see capsule summary HRSC-33.

The significant points made in this paper are the following:

1. Structural components having low vibration frequencies would probably be excited more efficiently by waves of longer duration.
2. The excitation of building structural components having high-frequency responses would also tend to be less for waves having longer rise times.
3. In a room with a window the internal pressure transient has a relatively small amplitude and is damped out rather quickly when the window is closed. On the other hand, when the window is partly opened by a particular amount, the duration of the inside pressure transient is markedly longer and the peak pressure value actually exceeds that of the outside exposure.
4. Results of flight-test measurements show that there is a general trend of increased building wall acceleration level with increased overpressure.

This is a good brief review of the structural effects of sonic booms.

SR-43
A SONIC BOOM INDEX AND STRUCTURAL REACTION TO IMPULSIVE NOISE
T. H. Higgins
FAA Staff Study, April 23, 1968

A sonic boom index is presented in this paper for use in predicting structural reaction to sonic booms. This index is defined as follows:

$$\text{Sonic Boom Index} = \frac{K\Delta P}{t}$$

Where K = arbitrarily assigned value to reduce size of index
ΔP = overpressure in lbs/sq. ft.
and t = rise time in seconds

The definition of this index was based upon the hypothesis that it is the integrated energy of the sonic boom which is important in determining structural reaction; the integrated spectral energy varies with the maximum overpressure and inversely with the rise time of the wavefront.

Data given in an earlier paper by Blume, et al (see capsule summary SR-39) are used to obtain total displacement and maximum fore and aft displacement distances resulting from sonic booms of varying overpressures and rise times. The overpressure (ΔP) and rise time (t) data are used to obtain the Sonic Boom Index (BI) of each sonic boom. The formula $BI = .05\Delta P/t$ was used. The structural reaction was then correlated with the B.I. It was found that the total racking displacement and the maximum fore and aft displacement in the direction of the flight track of the roofline of a two-story house decreases by one-half when the rise time doubles for sonic booms of equal overpressure. It is concluded that, as hypothesized, the structural reaction to sonic booms varies directly with maximum overpressure and inversely with the rise time. Therefore, the sonic boom index has merit for use in predicting structural reaction.

In another paper (see capsule summary HRSC-37) Higgins discusses the merits of using the Sonic Boom Index for predicting human response to sonic booms.

SR-44

PENETRATION OF SONIC BOOMS INTO THE OCEAN

Robert W. Young

Paper Presented to Acoustical Society of America, Ottawa, May 26, 1958

The results of a flight test experiment conducted to determine the attenuation of sonic booms as they propagate downward from the surface of the ocean are presented in this paper. The booms were generated by F-8 fighters diving to attain Mach 1.1 or 1.15 at an altitude of about 3000 feet. The flight tracks of the aircraft were at various distances from the observation point.

To measure the pressure signatures one microphone was mounted on a drifting sailing vessel 12 feet above the water surface, and a hydrophone was floated off to a depth of 160 feet. On a small boat a microphone was mounted at an average height of 1 foot above the water, and two additional hydrophones were positioned at -20 feet and -80 feet.

The results showed that the peak sound pressure level of the sonic boom from an F-8 aircraft has an octave-band spectrum that slopes downward 2 or 3 dB/octave, whereas the time-integrated octave band level (obtained by filtering a signal proportional to the original sound pressure p into an octave band (frequency limits 1 and 2) to p_{12}, squaring to get p_{12}^2, and then integrating with respect to time) slopes downward about 5 dB/octave. In water the peak sound pressure level, above 125 Hz, at a hydrophone 20 feet deep was found to be about 25 dB less than that in air; the integrated level was found to be 20 or even only 15 dB less than that in air. The reductions in sound pressure level at a depth of 160 feet were about 5 dB in addition.

SR-45

THE RESPONSE OF A SIMPLY SUPPORTED PLATE TO TRANSIENT FORCES; PART I - THE EFFECT OF N-WAVES AT NORMAL INCIDENCE

Anthony Craggs

NASA CR-1175, September 1968

A numerical method for determining the response of a structure to transient forces of arbitrary form is presented in this paper. This method is used to evaluate the response of a simply supported plate to an N-wave at normal incidence.

In order to obtain a numerical solution to an arbitrary forcing function, the forcing function is divided into a finite number of segments of equal duration. Each segment is then treated as an impulse and the net response is built up by the process of superposition. Once the forcing function has been idealized into a finite number of rectangular pulses, the total response is found by superimposing, with the appropriate time lag, the response from each one.

This technique is then applied to the response of a simply-supported plate to sonic booms. The response parameters studied are the displacement, acceleration, and stress at a point on the plate. Different load conditions are investigated by changing the rise time and duration of the boom. In obtaining a solution to the equation of motion of a uniform plate in forced vibration, a normal mode approach is used and any damping present in the system is assumed not to couple these modes. It is also assumed that the plate is vibrating in a vacuum so that there is no acoustic back pressure acting.

As a result of this investigation the following conclusions were reached:

1. Effect of Period Ratio τ/T (τ is the pulse duration and T is the natural period of the plate: The maximum amplification factor occurs when τ/T is unity and in this condition the maximum value is sensitive to a variation in the rise time. The greatest magnification factor for displacement is 2.6.

2. Effect of Rise time: When τ/T equals one, the maximum amplification factor occurs when the rise time is 1/4 of the duration of the pulse. It is then about 2.6. For zero rise time the amplification factor is about 2.1.

3. For the plate (aspect ratio 1.5) there is little difference between the displacement and stress time histories as these were almost completely dominated by the fundamental mode. However, the accelerations are affected more by the higher modes and, consequently, the response contains more peaks.

4. Under certain conditions the response for the time $t > \tau$, (i.e., when the system is left vibrating freely) is very small. This is dependent more on the overall shape of the pulse and its relation to the fundamental period of the system than to any other single parameter.

In Part II of this report (see capsule summary SR-48) the response of a simply-supported plate to N-waves at oblique incidence is analyzed.

SR-46

SONIC BOOMS RESULTING FROM EXTREMELY LOW-ALTITUDE SUPERSONIC FLIGHT: MEASUREMENTS AND OBSERVATIONS ON HOUSES, LIVESTOCK AND PEOPLE

C. W. Nixon, H. K. Hille, H. C. Sommer, and E. Guild

Aerospace Medical Research Laboratories, Wright-Patterson A. F. Base, Ohio, Report No. AMRL-TR-68-52, October 1968

In the flight test experiment discussed in this paper sonic booms generated by F-4C aircraft flying low-level terrain-following profiles during Joint Task Force II operations near Tonopah, Nevada were recorded under and near the flight tracks, and responses of structures, animals, and people were observed. Only the structural response findings will be discussed here. For a discussion of the human response and animal response results, see capsule summaries HRSC-89, and AR-4, respectively.

Peak overpressure levels ranged from 80 psf to 144 psf directly under the flight track and from 50 psf to 118 psf at various distances to the side of the ground track. Observed structures in the exposed residential areas consisted of very old frame and brick buildings in poor states-of-repair and both old and new campers and trailers. The poor conditions of the structures prior to test, the small number of them as well as the lack of overpressure data at the sites of the structures precluded relating overpressures to responses of specific types of construction.

Damage to structures was principally confined to glass breakage, plaster cracking, and furnishings falling from shelves. In almost all cases glass breakage occurred at the side of the building facing the approaching aircraft. There was no damage to the trailers.

It was felt by the authors that the most important knowledge gained from this experiment was that window glass fragments were propelled in some instances for distances of approximately 12 feet by the booms generated by the F-4C. Such an occurrence had never before been observed.

Other damage observed included the shattering of an already cracked safety glass in an older station wagon. A relatively new station wagon located 50 feet from the flight track incurred no breakage throughout the tests, although covers for the dome light and spare tire compartment popped out during sonic boom exposures. The small side window of a camper parked about 100 feet from the flight track broke and glass flew out as far as 12 feet in the direction from which the aircraft approached. In a small building about 200 yards from the track the receiver of a wall telephone was repeatedly shaken off its cradle by the booms and some light bulbs inside the optical tracking station were broken.

The findings of this investigation were qualitative rather than quantitative, in contrast to several previous investigations, such as the Oklahoma City tests, the White Sands tests, and the Edwards Air Force Base Tests (see capsule summaries SR-12, SR-16, and SR-39, respectively). Those three tests were much more extensive than the one discussed in the present paper, and the test structures were instrumented, in contrast to those of the present investigation. However, the overpressures of the present experiment were much larger than in any of the three previous tests. Therefore, the results of this investigation are significant in that they do provide an indication of the types and magnitude of damage that can be expected as a result of extremely large overpressures.

SR-47
RESEARCH ON CRITICAL STRUCTURAL RESPONSE TO THE SONIC BOOM
R. L. Lowery
NASA CR-66750, December 1, 1968

This report documents the results of a study of the structural damage potential of the sonic boom. The project was directed by Dr. R. L. Lowery. The major part of the work was done as a doctoral dissertation by T. V. Seshadri, which is documented in Appendix A.

The primary objective of this study was to determine the characteristics for the hypothetical "most critical" structure. Several different problem areas were involved in this search:

1. Determining a lumped parameter representation for the structural systems.

2. Determining the damping mechanisms of the structures and reasonable values for the damping coefficients.

3. Determining in what way the number of degrees of freedom of motion affects the severity of the response.

4. Determining how the predicted response compares with available field data.

A lumped parameter modeling system was derived in which the window or flexible panel was replaced by a lumped mass and an equivalent spring and damper. In this particular model the deflection of the system was preserved as was its damping factor and natural frequency. The lumped parameter model agreed mathematically with the continuous model for first mode response for simply-supported plates.

Damping mechanisms of mechano-acoustical systems were studied in three different ways:

1. Analytical study of the damping of Helmholtz resonators and rectangular panels.

2. Experimental measurements of damping of a small acoustical resonator.

3. Field measurements of 99 storefront windows, as mounted.

Although the agreement between experiment and theory was good for the Helmholtz resonator it was found to be poor for windows because of the effects of mechanical friction in the mounting. However, the damping studies served the purpose of identifying a reasonable value for the damping coefficient for use in the equivalent lumped parameter model.

The critical structural configurations for sonic boom response were isolated by first studying the general transient response spectra of undamped systems having varying degrees of freedom and then by finding the structure that most closely fit the equation.

The comparison of a limited amount of field data, recorded at Edwards Air Force Base (see capsule summary SR-39), with theoretical values was undertaken but the results were somewhat inconclusive.

The following conclusions were reached as a result of this study:

1. The most critical linear configuration for response to the sonic boom is a room having one large window and a properly tuned port. The largest magnification factor to be expected for an actual window installation considering realistic damping values is 7.0.

2. A large room having a flexible unit roof and one large window can exhibit a magnification factor of 3.5 for the response of the window.

3. A damping factor of 0.03 is representative for store front windows.

4. The theoretical damping factor of a plate in an infinite baffle is a function only of its aspect ratio. The reradiation damping, however, is insignificant when compared to the damping produced by edge effects and by mechanical friction.

5. Large windows must be driven well into their nonlinear regions before failure occurs. Under these conditions a hardening "nonlinearity" is manifested having the effect of limiting the maximum displacement.

SR-48

THE RESPONSE OF A SIMPLY-SUPPORTED PLATE TO TRANSIENT FORCES; PART II: THE EFFECT OF N-WAVES AT OBLIQUE INCIDENCE

Anthony Craggs

NASA CR-1176, 1968

In this paper a numerical method is used to compute the response of a simply-supported plate to an N-wave arriving at oblique incidence. In the first part of this study the response of a plate to a normally incident transient pressure loading was computed (see capsule summary SR-45). That work is extended in the present paper by considering the response of a structure to a travelling wave, which is more representative of the general case of sonic boom excitation than the normal incidence case. The method used is a simple extension to that used in part one of the study (see capsule summary SR-45 for details).

The factors influencing the response of the simply-supported plate to an N-wave arriving at oblique incidence are shown to be: (i) the ratio of the pulse duration to the fundamental period of the plate, and (ii) the convection forcing terms, which are different for each mode. It is also shown that asymmetric modes are excited, which do not make any contribution when the wave is at normal incidence to the plate. The computed results show that both the convection terms and the asymmetrical modes make a significant contribution to the form of the response for the displacements, velocities, and accelerations, though their effects are more dominant in the accelerations than for any other parameter.

An analysis of panel response to sonic boom N-waves at both normal and oblique incidence was made in earlier papers by Crocker (see capsule summary SR-41) and by Cheng and Benveniste (see capsule summary SR-28).

SR-49

SEISMIC WAVES GENERATED BY SONIC BOOMS: A GEO-ACOUSTICAL PROBLEM

A. F. Espinosa, P. J. Sierra, and W. V. Mickey

Journal of the Acoustical Society of America, Vol. 44, No. 4, 1968, pp. 1074-1082

Observations of seismic waves generated by sonic booms are presented in this paper. These waves were generated on different occasions by jet fighter planes flying in a climbing attitude at high altitudes.

The seismic waves coupled from sonic booms are explained in terms of a constructive interference phenomenon in the superficial ground layers. The effect of the sonic boom is simulated by a succession of very small impulses which are impinging the earth's surface at successive intervals of time along the path of the plane trajectory. Each of these impulses gives rise to a train of waves.

According to the ray-energy approach, constructive interference of the energy is possible only for those waves whose phase velocity equals the speed of sound. The apparent surface velocity, or phase velocity, of the sound wave and seismic waves must be equal in order for efficient and effective coupling to occur. When this is the case, the transfer of energy from the "acoustical mode" into the "elastic mode" takes place.

The experiments studied in this investigation took place at Cape Kennedy. The recordings were made using a geophone array containing up to 12 short-period vertical component stations, and a singular station recording the transverse and radial type of motion. The excitation of seismic coupled waves with different frequencies took place when fighter airplanes were flying in a climbing attitude over the Cape Kennedy area. A correlation was made between the acoustical signal registered at the microphone stations in Cape Kennedy and the first impulsive onset of the seismic waves recorded at the array setup.

The observed seismic waves were found to have the following characteristics:

1. The phase velocity of the impulsive onset was higher than the velocity of sound.
2. A single frequency excitation was observed by efficient coupling of the acoustical mode to the elastic mode.
3. The frequency was almost constant, increasing very slightly as time increased.
4. The amplitudes of the coupled seismic waves increased to a maximum and then decayed monotonically as time increased.
5. A higher-mode propagation was observed and was identified as a third shear mode, overriding a longer-period coupled seismic wave.

It is pointed out that one of the immediate applications of this coupling effect is the possibility of using this phenomenon as an efficient tool in determining superficial earth structure. Furthermore, it is suggested that, under certain circumstances, it might be possible that seismic waves of damaging proportions could be generated, thus creating a structural hazard as supersonic and hypersonic flights increased. However, in an earlier investigation (see capsule summary SR-23) Baron, et al, concluded that the possibility of surface waves in the ground causing damage to structures is very remote. The results of a later investigation by Goforth and McDonald (see capsule summary SR-50) also led to that conclusion.

SR-50

SEISMIC EFFECTS OF SONIC BOOMS

T. T. Goforth, J. A. McDonald

NASA CR-1137, 1968

Results are presented in this paper of an experimental investigation in which earth particle velocities produced by sonic booms were recorded at Edwards Air Force Base, California, the Tonto Forest Seismological Observatory near Payson, Arizona, and the Uinta Basin Seismological Observatory near Vernal, Utah. Portable seismograph systems were used for measurements at Edwards AFB. At the other two locations the observatory seismograph systems were utilized in addition to the portable systems. Geologic studies, including seismic refraction surveys, were conducted at each of the three test sites. The particle velocity data were analyzed visually and automatically, and the results were correlated with geologic data and with NASA-furnished overpressure, flight parameter, and meteorological data. Theoretical estimation techniques were developed to predict maximum particle velocities to be expected for the passage of a known sonic boom at a particular geological location.

The following conclusions were reached as a result of this study:

1. The maximum ground particle velocity produced by a sonic boom is linearly related to the maximum overpressure of the boom in the range of overpressures between 0.5 and 5.0 pounds per square foot. Experimental results indicate that each pound per square foot of overpressure produces about 100 μ/sec peak particle velocity on low-density rock and about 75 μ/sec on high-density rock.

2. A theoretical estimation technique based on the elastostatic deformation of a half space gave good agreement with experimental results for the peak particle velocities resulting from a given N-wave acting on a particular geology.

3. The damage potential of the peak particle velocities produced by sonic booms is well below damage thresholds accepted by the United States Bureau of Mines and other agencies.

4. Peak particle velocities recorded on the lateral edge of the sonic boom pressure envelope are attenuated by a factor of 6 relative to particle velocities observed under the aircraft.

5. Focusing of seismic energy due to backward propagation from the hyperbolic intersection of the shock cone and the ground was not observed.

6. Peak particle velocities recorded at a depth of 44 feet were attenuated by a factor of 75 relative to those recorded at the surface.

7. Good evidence for the existence of velocity-coupled Rayleigh waves was found for one recording station. The lateral uniformity of near-surface layering and velocity distribution necessary for such waves to build up sufficiently to constitute a menace to structures makes such an occurrence unlikely.

Extensive studies involving the seismic effects of sonic booms were also made by Baron, et al (see capsule summary SR-23) and Espinosa, et al (see capsule summary SR-49). The study by Baron, et al was primarily of a theoretical nature, while that of Espinosa, et al was primarily experimental in nature.

SR-51
UNDERWATER SOUND PRESSURE FROM SONIC BOOMS
R. N. Sawyers
Journal of Acoustical Society of America, Vol. 44, No. 2, 1968, pp. 523-524

In this article an expression is derived for the sound pressure in a homogeneous fluid half-space, the surface of which is loaded by an N-wave. The expression is derived from the wave equation together with a boundary condition on the pressure at the water-air interface which is determined by the sonic boom pressure signature. The expression for the pressure is then cast into dimensionless form and plotted as a function of time at three selected depths. It is shown that the peak pressure attenuates rapidly with depth. Also, in contrast to the abrupt beginning and end of the sonic-boom pressure variation in air, the pressure wave under water is seen to exhibit a precursor and tail.

In a later experimental investigation (see capsule summary SR-66) Waters and Glass verified the essential validity of the theory developed in this paper. The results of a ballistic investigation by Malcolm and Interieri also were in agreement with the theory developed here.

SR-52
DAMAGE EXPERIENCE
William F. McCormack
Proceedings of the Conference, Noise as a Public Health Hazard. Washington, D. C., June 13-14, 1968, in The American Speech and Hearing Association Reports No. 4, February 1969, pp. 270-277

The results of Air Force experiences in handling sonic boom damage claims are discussed in this paper. The discussion deals, in a general way, with the manner in which damage claims are processed, and it summarizes the number and types of complaints received and the amount of money actually paid for damages.

The main difficulty found in processing claims is that mysterious damage of unknown or unexplained origin will frequently be blamed on sonic booms if a boom has occurred anytime near the time of damage (and sometimes even if it has not). Only the claimant knows what his property looked like prior to the sonic boom. Often, only the claimant is able to furnish the circumstances under which the damage was discovered. Usually, only the claimant or those in his immediate vicinity are able to describe the intensity of the sonic boom at that particular point. Thus, much of the processing of a sonic boom claim involves consideration of the subjective opinions and observations of persons whose impartiality and legal credibility are always in question. The Air Force, in its investigation, must identify the aircraft as of likely Air Force origin and in some cases must utilize the services of an expert, such as an engineer, to ascertain the cause of damages. In addition, policy guidance has been formulated by the Air Force based upon the results of scientific tests to advise investigators and claimants generally as to what damage may ordinarily be caused by a sonic boom.

The Air Force system for processing damage claims proceeds as follows: A complaint of damage may be presented in any manner to the nearest Air Force base claims office. There are approximately 140 scattered throughout the United States. An Air Force claims officer, who must be a lawyer, will then send the claimant claim forms and instructions on presenting a claim and also conduct, or supervise, an investigation into the cause of damage. It has been Air Force experience that out of approximately every three persons complaining of damage and who have been sent the claim forms, only one will actually present a claim.

In the event that a sonic boom damages glass, the Air Force will pay for the reasonable cost of replacement. Payment for plaster damage, however, is limited to a maximum of 50% of the cost of repair, including painting, based upon Air Force experience that sonic booms will not cause damage to new plaster. Exceptions to this policy are made for such rare situations as when green, newly-set plaster is damaged as a result of a sonic boom.

The table below, which was taken from this paper, presents a list of claims for sonic boom damage in all types and categories which have been presented to the Air Force since 1956. Many of these claims for the years prior to 1960 involved specific accidental low-level incidents. It can be seen from this table that over a third of all sonic boom damage claims since 1956 have been approved in whole or in part.

Fiscal Year	*No. of Claims*	*Dollars Claimed*	*Approved in Whole or Part*	*Dollars Approved*
1956	36	$ 12,000	$ 21	$ 2,000
1957	372	157,000	286	19,000
1958	522	196,000	235	40,000
1959	632	285,000	243	21,000
1960	681	108,000	227	20,000
1961	1,146	703,000	527	57,000
1962	3,092	930,000†	1,451	132,000
1963	7,200	4,023,000	2,268	239,000
1964	5,102	3,545,000	1,664	163,000
1965	9,374	4,935,000	2,493	255,000
1966	4,856	3,284,000	2,123	211,000
1967	2,216	1,732,000	1,090	145,000
1968*	3,051	2,236,000	1,276	135,000
Total	38,483	$ 22,209,000	$ 13,193	$ 1,460,000

* Ten months only
† Rounded to nearest thousand dollars

Summary of sonic boom claims presented in the United States to the Air Force

The paper goes on to summarize the claims resulting from various sonic boom field tests, such as those at Oklahoma City (see capsule summary HRSC-14. It also discusses personal injury claims and claims involving damage to animals.

The study showed that the number of cases of personal injury and injury to animals was extremely low. There were 3.5 cases of personal injury per 1000 claims on a nationwide basis in 1966. For animal injuries the rate was 13 per 1000 nationwide in 1966. It is pointed out that most of the claims for personal injury received by the Air Force have been of an indirect nature. The claims usually involve such incidents as persons struck by falling objects or having been startled into injuring themselves. Although occasional claims for loss of hearing, nervousness, or shock have been received without accompanying physical contact, these claims have not been favorably considered.

This paper gives an excellent summary of the extent of damage claims in the United States during the period 1956-68.

SR-53
DYNAMIC RESPONSE OF STRUCTURAL ELEMENTS EXPOSED TO SONIC BOOMS
D. H. Cheng, J. E. Benveniste
NASA CR-1281, March 1969

A summary of analytical results on the subject of dynamic response of structural elements exposed to sonic booms (see capsule summaries 28, 40, and 41, for example) is presented in this report. The structural elements of interest are uniform beams and plates with various boundary conditions. The disturbances are represented by a variety of boom signatures which approximate those obtained from field measurements. Responses of structural elements to a unit impulse and to a unit force are first obtained. This enables a comparison to be made of the relative dynamic effects of an N-shaped pressure pulse and an N-shaped traveling wave on a simple structure. It is followed by a study of the effects of boundary restraints using an N-shaped pressure pulse.

Based on the results due to such idealized boom signatures as sine pulse, half cosine pulse, triangular pulse, N-shaped pulse, and N-shaped pulse with spikes, two simplified methods in evaluating sonic boom effects on structural elements are proposed: One requires only the knowledge of the peak pressure and the other, the positive impulse. Neither requires the specification of the exact shape of the boom signature.

The above methods are shown to be very simple to use and are applicable to structural elements which are always in contact with the supports. As shown in an earlier paper by Benveniste and Cheng (see capsule summary SR-40), considerably higher dynamic effects can be expected in the unusual case where the structural element is loosely bound to its supports and can therefore rattle in the wake of sonic boom disturbances. Depending on the relative stiffness of the structural element and its support and other factors, the dynamic shear may increase much more rapidly than the dynamic moment. As a result, the tensile stress induced by shear at the supports may become the dominant cause for damage in structural elements made of brittle construction material. This is illustrated in the appendix by a rattling beam subjected to an N-shaped pulse.

This is a good brief summary of the state of the theory as of 1969 concerning the dynamic response of structural elements to sonic booms.

SR-54
SONIC BOOM DAMAGE TO STRUCTURES
J. H. Wiggins, Jr.
Institute of Environmental Sciences, Engineering Societies Library, April 20, 1969, pp. 189-197

This paper deals with the prediction of the type, amount and nature of damage that can be expected from supersonic aircraft overflights. Three basic methods are presented for studying and predicting such damage. These are the "inductive approach," the "deductive approach," and the field test method.

The inductive approach involves the separate study of interdependent parameters from boom to damage. Knowing specific aircraft design, weather, and flight conditions, the free-field wave characteristics can be predicted. The structural design variables can then be used to construct loading functions and applied to a structure having certain size, mass, stiffness, and damping characteristics. Thus, the maximum structural response achieved during the dynamic loading period or effective static load can be derived. If the material strength and the strength-reducing or stress-raising conditions present in each element are also known, then a damage prediction from the supersonic aircraft considered can be made. With an appreciation for the damage that can be expected from individual elements as well as the distribution of each element throughout the overflight pattern, a prediction of total damage can be made.

The deductive approach involves the overflight of cities by certain supersonic aircraft, which produces damage claims. These, upon investigation and analysis, result in some idea of the damage to be expected from these aircraft. By relating this damage expectancy to the supersonic aircraft in question, damage to particular categories of structural elements can be predicted. Knowing the structural distribution along the overflight path allows a total damage prediction per flight to be made.

A third method for evaluating damage is to conduct limited field tests in which engineers make condition surveys prior to and after an overflight. Results of these types of studies are shown to be in good agreement with those of the other two methods.

It is concluded that it is possible to predict with limited but reasonable accuracy the type, amount, and nature of damage that can be expected from super-supersonic overflights using both inductive and deductive means of analysis as well as test results.

SR-55

BUILDING VIBRATIONS DUE TO AIRCRAFT NOISE AND SONIC BOOM EXCITATION

H. D. Carden, D. S. Findley, and W. H. Mayes

American Society of Mechanical Engineers, 69-WA/GT-8, Paper Presented at ASME Annual Winter Meeting, Los Angeles, Calif., Nov. 16-20, 1969

The results from investigations of the vibration response characteristics of residential type structures to sonic booms and aircraft noise are presented in this paper. Only the results concerning sonic boom effects will be summarized here. The data upon which the investigation is based were obtained in the Edwards Air Force Base sonic boom experiments (see capsule summary SR-39).

An analysis of the low frequency boom induced motions showed that the modes involve the diaphragm motions of the walls, floors, and ceilings. The response patterns were found to demonstrate strong structural interactions, which may have involved both the structure and the trapped air in the rooms, resulting in preferred model patterns involving not only adjacent components, but also those located remotely. The forced excitation results also indicated that, since the fundamental frequencies associated with walls of different width occur in a rather narrow frequency band, the structural interactions are enhanced.

For a much more extensive discussion of the structural response results obtained in the Edwards AFB tests see capsule summary SR-39.

SR-56

AN EXPERIMENTAL ASSESSMENT OF THE POSSIBILITY OF DAMAGE TO LEADED WINDOWS BY SONIC BANGS

F. L. Hunt

Royal Aircraft Establishment, Technical Report 69282, December 1969

In the investigation described in this report leaded windows were exposed to simulated sonic booms generated using the explosive technique developed by Hawkins and Hicks (see capsule summary SM-2). An array of leaded windows were used in the test. A plain glass window was included in the array so that its vibration response to booms could be compared with that of the similar sized leaded window that was next to it, and so that glass stresses could be compared between the two windows. The size of the windows is not given. The plain window was of 32 oz. glass, which is about 0.15 in. thick. The larger central panes of the leaded window were 24 oz. glass, which is 0.1 in. thick, while the edge panes were of 32 oz. glass.

The leaded windows were supported by steel saddle bars of 0.375 in. square section. The ends of these were firmly fixed into the window frames and wired to the lead strips of the windows in the conventional manner. One of the saddle bars associated with the weakest window was purposely omitted so that the vibration of the window at that point could be compared with the vibration of the conventionally supported part of the same window. The windows were fixed by wood beading into a strong timber frame that was fitted into a brick building which was specially erected on the test site.

The windows were subjected to a total of 25 explosive simulated sonic booms, the maximum overpressure being 5.0 psf. The windows, including the one which was in poor condition before the tests, were in no way damaged by the booms. It was found that the booms caused lower strains in the glass of a leaded window than in the plain glass window of the same size. No cumulative and permanent distortion of the leaded windows was observed as a result of the simulated booms, but it was felt that more research on this particular topic was needed.

The leaded windows were found to have high inherent damping. As a result, it is concluded that their susceptibility to extra damage due to coincidence effects between typical sonic boom durations and window natural period is very low.

It was found that the deflection of the window having the saddle bar removed from one side was twice as much on the side having no saddle bar as on the side with the saddle bar. As a result of this finding it is concluded that, if the risk of damage is to be minimized, the fixings of the bars and the wire attachments must be maintained in good condition.

A later paper by Hunt (see capsule summary SR-60) presents the results of an investigation in which leaded windows were exposed to an actual sonic boom. No damage to the windows was observed in that experiment either.

This was a significant investigation, since previous to it very little was known concerning the effects of sonic booms on the type of glass used in church windows.

SR-57

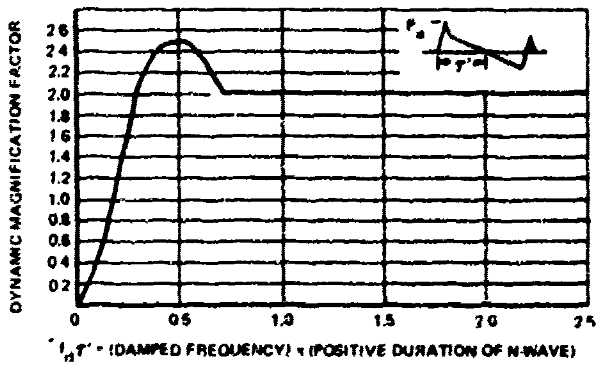
STRUCTURAL RESPONSE TO SONIC BOOMS

M. J. Crocker and R. R. Hudson

Journal of Sound and Vibration, Vol. 9, No. 3, 1969, pp. 454-468

In this paper the response of a damped spring-mass system to an N-wave is examined. In particular, the dependence of the response upon the rise time of the N-wave, upon the ratio of total to positive phase duration, and upon structural damping is determined. The cases of response to N-waves with shock reflection and to repeated N-waves are also studied.

The results are given in terms of dynamic magnification factors. For any particular value of the non-dimensionalized frequency $f\tau$ (here f is the undamped resonant frequency of the system and τ is the duration of the positive phase of the N-wave), the dynamic magnification factor is defined as the greatest maximum or minimum value of the normalized displacement which can occur. It is so named because it represents the ratio of dynamic displacement of the system to the displacement that would occur under a static load equal to the peak overpressure of the sonic boom. It is shown that increasing the values of s, r, and u (here s is ratio of total to positive phase duration, r is the ratio of N-wave rise time to τ, and u is the ratio of the reflection shock pulse length to τ) tends to produce higher dynamic magnification factors and to cause some shift in the non-dimensionalized frequency $f\tau$ at which peak responses occur. However, increasing values of structural damping ratio ζ are shown to cause a marked decrease in response, particularly for free motion as $f\tau$ increases. A final curve incorporating these findings of dynamic magnification factor versus $f\tau$ was plotted which envelopes the effects of varying positive to negative phase duration, rise time, shock reflections, and structural damping. In drawing this curve, upper values of s, r, and u and a representative value of δ were chosen. This curve, which is shown below, may be used to determine the possibility of damage due to overflights of a supersonic transport.



Envelope of dynamic magnification factor curves for use in assessing possibility of damage due to supersonic transport overflight

In a later paper (see capsule summary SR-76) P. deTricaud measured the natural frequencies of building partitions and windows. Those results can be used together with the results of the present paper to get a quick rough calculation of the manner in which these particular structural elements will respond to a particular sonic boom signature.

This study formed the basis for most subsequent investigations involving the use of dynamic magnification factors.

SR-58
RESPONSE OF BOX-TYPE STRUCTURES TO SONIC BOOMS
Neil Popplewell
Ph.D. Thesis, University of Southampton, Institute of Sound and Vibration Research, 1969

Experimental and computational methods are presented in this thesis which determine the response of a box-type structure to traveling arbitrarily shaped sonic boom waves. The computational method assumes that the pressure inside the structure can be neglected. Thus, there is no internal acoustic coupling between structural subelements. In order to assess the limitations of this assumption, the magnitude of the pressure inside the structure must be known. This internal pressure usually provides an additional contribution to the stiffness of each individual structural subelement. The most flexible subelements will be most affected by the internal pressure. Hence, the present theory is mainly applicable to the response of the stiffest subelements such as walls and ceilings, rather than flexible subelements such as windows.

The free vibration characteristics of a simple box-type structure were evaluated using rectangular finite elements and the results were compared with an exact solution. Excellent agreement was found for the natural frequencies and mode shapes when only a small number of elements were used in the box's idealization.

This method was extended to determine the time history of the mathematical model's response to a traveling wave. The theoretical results were compared with the experimental response of a physically scaled down model to a simulated sonic boom. The comparison indicates that reasonable theoretical estimates of the experimental model's response to a traveling wave can usually be obtained with a minimum description of the wave and model characteristics. Discrepancies occur, however, when a traveling wave has a small pressure component at a frequency corresponding to the natural frequency of a significant mode. Under these circumstances, the experimental model's response is extremely sensitive to small changes in the internal pressure, traveling wave or model characteristics.

The main difference between the theoretical and experimental models' responses was found to be due to an inadequate theoretical description of the wave's flow over the model. In particular, the theoretical description of the flow over the model's back face was found to be much too simplified. Consequently, the greatest discrepancy between the experimental and theoretical results occurred on this face.

The following are some of the conclusions reached as a result of this study:

1. A detailed investigation of the variation in overall peak acceleration showed that it tends to decrease with increasing λ/L (here λ is the free-field wavelength of sonic boom and L is the maximum structural length in the direction of the sonic boom's propagation). This was found to be the case for both the experimental model (open and closed boxes) and the full scale structure.

2. The experimental peak accelerations of the closed model can be seven times greater than its peak accelerations due to a unit, instantaneous step pressure acting on all faces.

3. The greatest acceleration of any face always occurs when the N-wave is acting normally to that face.

4. Introducing a large opening into the model's front face can increase the peak accelerations of the back and side faces by a factor of two. This amplification is due to the increased internal pressure.

5. The peak acceleration tends to be independent of the sonic boom's excitation frequency, convection and angle of incidence at low excitation frequencies.

6. The rise time of the sonic boom is significant. Its effect is mainly restricted to the structure's front face. Decreasing the rise time increases the peak acceleration of the front face.

7. The most important parameter at intermediate excitation frequencies is the degree of matching between the structure's natural frequencies and the sonic boom's excitation frequency. There may be an upsurge in the structure's peak accelerations when the excitation frequency is similar to any one of the structure's natural frequencies.

8. The wave's convection is most significant at high excitation frequencies.

Many previous investigations had been conducted dealing with the response of individual structural elements, such as beams and plates, to sonic booms. See capsule summaries SR-28, SR-40, SR-41, SR-45, SR-48, SR-53, and SR-57). However, the present investigation was the first to develop a theory describing the response of a complete box-type structure composed of such elements to sonic booms.

SR-59
THE EFFECTS OF SONIC BOOM
J. H. Wiggins, Jr.
J. H. Wiggins Co., 1969

This handbook was developed in conjunction with a course whose purpose was to acquaint civil engineers with the theory of sonic booms and their effects on structures so that these engineers could process boom damage claims fairly and efficiently. A general description is given of the materials important to sonic boom knowledge. Figures from various sonic boom reports were reproduced, referenced, and incorporated into the text to give a broad but concise picture of what the huge bibliography given at the end of the book contains.

The following topics are covered: (1) generation and propagation of sonic boom shock waves; (2) factors affecting the loading waveform; (3) the response of elastic structures to dynamic loads; (4) dynamic amplification factor spectrum; (5) the measured behavior of typical structural elements under various sonic boom conditions; (6) the statistical variation of sonic boom and damage evaluation procedures; and (7) suggested procedures for inspecting and evaluating sonic boom damage claims.

This is an excellent summary of the state of knowledge as of 1969 concerning structural response to sonic booms.

SR-60
THE RESPONSE OF LEADED WINDOWS IN WISBECH PARISH CHURCH TO SONIC BANGS
F. L. Hunt
Royal Aircraft Establishment, Technical Report 70029, February 1970

In this investigation the response of three leaded windows in various states of repair to an actual sonic boom was measured. The sonic boom had a free field effective overpressure (obtained from the recording by extending the essentially straight, sloping line between the bow and stern shocks to the onset of the bow shock) of 1 psf and a signature interval of approximately 100 ms. The recorded effective overpressure on the wall of the church in which the leaded windows were mounted was 2 psf.

None of the three windows, one of which was in very poor condition, appeared to be damaged by the boom. However, the author points out that there is still the possibility that continued exposure to frequent sonic booms will accelerate a window's gradual deterioration that is caused by weather and the window's noise and vibration environment.

An earlier paper by Hunt (see capsule summary SR-56) presents the results of an investigation in which leaded windows were exposed to simulated sonic booms up to 5 psf in intensity. No window damage was observed in that experiment either.

This investigation was much too limited in scope to lead to any conclusive findings.

SR-61
MEASURED VIBRATION RESPONSE CHARACTERISTICS OF FOUR RESIDENTIAL STRUCTURES EXCITED BY MECHANICAL AND ACOUSTICAL LOADINGS
H. D. Carden, W. H. Mayes
NASA TN D-5776, April 1970

This report contains basically the same material as an earlier paper by Carden, Findley, and Mayes (see capsule summary SR-55). The reader is referred to that capsule summary for details of this work.

SR-62
LINEAR AND NONLINEAR RESPONSE OF A RECTANGULAR PLATE SUBJECTED TO LATERAL AND INPLANE SONIC BOOM DISTURBANCES
L. J. Knapp and David H. Cheng
NASA-CR-66936, April 1970

In this report the transient response of a rectangular window pane exposed to an N-wave is studied using both linear and nonlinear theories. The sonic boom causes a lateral disturbance in the form of an N-shaped pressure pulse and an inplane disturbance in the form of a sinusoidal pulse.

It is shown that in the linear theory the imposition of lateral and inplane pulses may be simultaneous or separated by a brief time delay. In addition there may be a static inplane load. Due to the inplane sinusoidal pulse, the equation of motion is of the Mathieu type. An improved procedure in solving Mathieu's equation is presented. The effects of the inplane static and dynamic loads, the pulse durations, and the time-lag are included in the study.

In the nonlinear theory, in addition to the usual simply-supported boundary conditions, two sets of inplane boundary conditions are specified: movable vertical sides and immovable vertical sides. For both sets of inplane boundary conditions, the longitudinal inertia of the plate is either neglected or considered by assuming that the longitudinal mass is concentrated at the top of the plate. The equations of motion are reduced to a set of ordinary nonlinear coupled differential equations by using the Galerkin method. These equations are solved numerically by Hemming's modified predictor-corrector integration method. The effects of the dynamic inplane load, the lateral overpressure, and the movable and immovable vertical sides are studied.

A comparison of the results obtained by using linear theory to those obtained using the nonlinear theory shows them to be almost identical for an N-wave overpressure of 1 psf. This was not felt to be surprising since the lateral deflection in this case is always less than 0.3 of the thickness of the plate. For an overpressure of 2 psf, however, it is found that the deflections obtained by the linear theory can be more than 10% larger than those obtained by the nonlinear theory. Therefore, the stresses predicted by the linear theory can be more than 10% off of those obtained by the nonlinear theory. It is concluded therefore that if a 10% error is tolerated, the linear theory gives acceptable results if the lateral deflection is confined to be less than one-half the thickness of the plate.

This report was the first to investigate the importance of nonlinear effects in the deflection of glass by sonic booms. Since, as shown by Wiggins (see capsule summary SR-21), the overpressures required to break properly mounted glass are usually much greater than 2 psf (except in the case of very large windows), the use of a linear theory to predict glass breakage due to sonic booms will be valid only for a limited class of windows, if the results of the present report are correct.

SR-63
PENETRATION OF A SONIC BOOM INTO WATER
R. K. Cook
The Journal of the Acoustical Society of America, Vol. 47, No. 5 (Part 2), May 1970, pp. 1430-1936

The analysis presented in this paper has two main purposes. The first is to find the sound-pressure distribution underwater caused by a sonic boom incident on the water surface. The second is to find the waveform of the wave reflected into the atmosphere from the surface of the water.

At speeds less than 1000 m/sec, the N-wave generated by an aircraft in level flight has an angle of incidence (on the water surface) greater than 19°. This minimum angle of incidence is greater than the critical angle for the passage of a sound wave from air into water, which is stated to be about 14°. Each sinusoidal component of the N-wave is therefore totally reflected from the surface and is accompanied by a plane wave in the water having a subsonic phase velocity, whose sound pressure amplitude decreases exponentially with depth below the surface.

The general procedure consists of the use of the Fourier integral method to solve the Cauchy problem posed by the sonic boom penetration into water. In the first step the reflected and refracted waves for an incident sinusoidal wave are found. The second step is to find the Fourier transform of the incident N-wave. Finally, the total reflected and refracted waves (caused by the N-wave) are found by linear superposition of the effects of the incident sinusoidal components.

Using the above procedure, expressions are derived which describe the sound field underwater and the reflected wave. The expressions indicate the following:

1. The penetration depth, comprising well over half of the underwater energy, is about the same as the length of the N-wave on the surface.

2. The analysis shows that the wave reflected into the atmosphere has (a) two infinitely large pressure spikes at the leading and trailing edges of the N-wave, and (b) a weak precursor and a weak tail. The same is true of the underwater wave just at the surface. The spikes, precursor, and tail have positive pressures and are even functions of distance from the center of the N-wave.

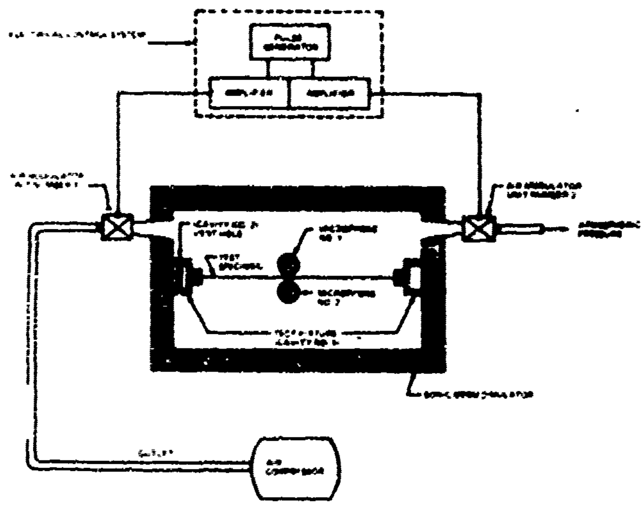
In an earlier paper (see capsule summary SR-51) Sawyers also derived an expression for the underwater sound pressure induced by sonic booms.

SR-64
AN EXPERIMENTAL STUDY TO DETERMINE THE EFFECTS OF REPETITIVE SONIC BOOMS ON GLASS BREAKAGE
G. C. Kao
Federal Aviation Administration Report No. FAA-NO-70-13, June 1970

The main objective of the program discussed in this paper was to determine the cumulative damage effect on glass of repetitive sonic booms. In order to evaluate such phenomena experimentally, a pneumatic-pistonphone simulator was developed and used successfully to test glass specimens under simulated sonic boom overpressures.

A schematic, which was taken from this report, of the sonic boom simulator is shown below. The shaping of N-waves in the simulator is achieved by modulating the airflow through the two airstream modulating valves (the inlet and outlet valves) under a constant compressor pressure. The essential part of the entire waveform synthesizing cycle is the shaping of the elec-

trical control signals used to generate a series of rapid interruptions of airflow through the valves. The simulator is capable of producing simulated sonic boom pressure signatures with rise times of 10-20 milliseconds, variable amplitudes of 1-100 psf, and variable durations of 50-400 milliseconds.



Schematic of simulator

The glass specimen dimensions were typically 48" x 48" x 3/32". Preliminary static strength tests were conducted on two sizes of new (previously unused) single strength glass to determine mean values and probability distributions of incipient failure pressures, and a few such tests were conducted for used (scratched and weathered) glass specimens. The results for the new glass static failure pressure of 25.6 psf and a standard deviation of 4.5 psf. For new glass 20" x 20" x 3/32" the mean static failure pressure was 239.0 psf with a standard deviation of 72.5 psf.

The emphasis in these experiments was on the cumulative damage from a large number of booms. The data obtained concerning this topic are shown in the table below, which was taken from this paper.

Test number	Net overpressure P, psf	Wave duration milliseconds	Number of booms applied	Remarks
1	40-48	162	1,400	No failure
2	22.5	400	40	Failure
3	13-16	400	10,000	No failure
4	24	400	87	Failure
5	18-20	400	400	Failure
6	18-20	400	436	Failure
7	13	400	37	Failure
8	19.5	400	2	Failure

Sonic boom test data of 48" x 48" x 3/32" glass specimens

Glass damage data

Based upon the above data the following conclusions were reached:

1. From the results of the repetitive test data it is clear that: the probability of glass damage to specimens subjected to overpressure levels of less than 4 psf is quite small; the endurance limit for specimens tested is estimated between 14 to 16 psf. But the statistical results suffer from statistical inaccuracy due to a small number of glass specimens tested. Hence, these data could not be utilized to formulate a statistical model to predict glass damage.

2. From the results of static test data it appears that the effects of natural environments reduce the breaking strengths of the used glass as compared to that recommended by current design practices.

3. It is feasible to apply the pneumatic pistonphone concept to generate pressure disturbances for simulating sonic booms. The pressure signatures can be controlled and reproduced reasonably well to synthesize various sonic boom waveforms. The simulator can be used efficiently to perform repetitive sonic boom testing of structural panels.

The results of this investigation are in qualitative agreement with those of the White Sands, New Mexico sonic boom tests (see capsule summary SR-16). In that flight test investigation 680 successive flights at overpressures of 5.0 psf were generated by B-58 and F-104 aircraft during one period of the study. No window damage was found as a result of the cumulative effects of these flights.

The rise times of the simulated sonic booms used in this investigation (on the order of 10 msec) are much longer than actual sonic boom rise times. However, since windows respond mainly to the low frequencies of the boom waveform, this large rise time may be acceptable. However, this remains to be determined.

SR-65

DIFFRACTION AND REFLECTION OF SONIC BOOM WAVES

B. M. Rao, G. W. Zumwalt

Journal de Mecanique, Vol. 9, No. 2, June 1970. pp. 309-324

In this paper an analytical method is developed to predict the pressure-time history of diffracted and reflected sonic boom waves in the vicinity of walls and corners. Sonic boom waves are represented as acoustic waves and a solution is derived for the acoustic wave equation. The theory is then applied to a particular problem to demonstrate its feasibility. The problem chosen was a commercial store building in Oklahoma City in which an 8' x 10' x 1/4" plate glass window was broken coincident with the occurrence of a sonic boom test in 1964. This particular boom was produced by an F-101 aircraft at 37,742 feet altitude on a steady course at a flight Mach number of 1.4. The resulting computed pressure time history on the broken window showed that the effects of diffractions and reflections were to increase the peak overpressure by 25% over that unaffected by the building geometry and to result in small pressure oscillations after the passage of the waveform.

SR-66
PENETRATION OF SONIC BOOM ENERGY INTO THE OCEAN: AN EXPERIMENTAL SIMULATION
J. F. Waters, R. E. Glass
Hydrospace Research Corporation Report No. HRC TR 288, June 1970

In the experimental investigation described in this report the penetration of sound into a body of wa· r from a simulated airborne sonic boom was measured. The experiment was acoustically scaled. Dynamite caps were used to produce spherically spreading N-waves which impinged upon the surface of a flooded quarry 80 feet deep and 300 feet wide. Microphones at the water surface and hydrophones at various shallow depths were used to measure the exponentially attenuating penetration of the airborne pressure field into the water, under total reflection conditions.

The portion of the shock wave which was involved in this experiment closely resembled a sonic boom in peak pressure amplitude, angle of incidence, and waveshape, but had a duration which was about 0.01 that of a typical sonic boom. It is shown that this means that the depths of penetration of energy from the shock wave into the water in the experiment were about 0.01 as great as would occur for an actual sonic boom incident upon the ocean surface.

The following conclusions were reached as a result of this investigation:

1. The experiment resulted in verification of predictions based on Sawyer's theory of N-wave penetration into a flat body of water under total reflection conditions (see capsule summary SR-51). Therefore, it is believed that the theory is valid, under the restrictions of the assumptions involved in its development.

2. The sound pressure spectrum levels associated with the penetration of sonic booms to various depths in the ocean were computed, based on Sawyer's theory. These predicted levels were compared with measured typical deep-ocean ambient noise spectrum levels over a wide range of frequencies. At depths of less than a thousand feet the sonic boom levels were appreciably higher than the corresponding ambient noise levels only at very low frequencies, from about 0.5 to 200 Hz. The spectrum levels at about 0.1 Hz of ambient pressure fluctuations due to surface waves were appreciably higher than the sonic boom peak spectrum levels.

3. The existing theory is limited in scope by a number of assumptions. The aircraft is assumed to be in horizontal flight at constant speed, less than Mach 4.5, over an extended interval of time. The ocean surface is assumed to be flat and the ocean itself to be homogeneous. Results apply only to a small region of the intersection of the sonic boom shock cone with the ocean surface. Finally, only symmetrical N-waves with zero rise times and linearly changing pressure amplitudes are considered. Despite the restrictive nature of these assumptions, the theory developed on this basis is believed to be appropriate for application to simple operational situations.

4. On the basis of the acoustically scaled simulatio , it is predicted that a ship on the ocean surface which is exposed to an atmospheric sonic boom will cause significantly more noise to go into the water in the region of the ship, than would have ordinarily penetrated into the water. The physical mechanism for this would be the acoustic excitation of the ship, which is a nearly closed air-filled cavity floating on the surface, followed by reradiation of a portion of the acoustic energy into the water. This reradiated noise would not be attenuated rapidly with depth and frequency, as would penetrating noise.

In an earlier paper (see capsule summary SR-44) Young presented the results of flight test measurements of sonic boom penetration into the ocean. However, no comparison of the results with theory was made in that paper.

This is a good experimental demonstration of the essential validity of Sawyer's theory.

SR-67
REPORT ON THE SONIC BOOM PHENOMENON, THE RANGES OF SONIC BOOM VALUES LIKELY TO BE PRODUCED BY PLANNED SST'S, AND THE EFFECTS OF SONIC BOOMS ON HUMANS, PROPERTY, ANIMALS, AND TERRAIN
Attachment A of ICAO Document 8894, SBP/II, Report of the Second Meeting of the Sonic Boom Panel, Montreal, October 12 to 21, 1970

This report is composed of six chapters, each dealing with a certain aspect of sonic boom phenomena. The present capsule summary summarizes only Chapter 4 and Chapter 6, which are respectively entitled "Sonic Boom Effects on Property" and "Sonic Boom Effects on Terrain."

Chapter 4 summarizes the results of the various structural response studies that have been conducted and some of the concepts involved in predicting structural reaction to sonic booms. The following are some of the conclusions reached as a result of this review:

1. Laboratory and controlled overflight experiments with monitored structures were generally negative as regards sonic boom damage from overpressures up to 20 psf; there was some extension of plaster and paint cracks. Controlled overflight with unmonitored structures in a range of nominal overpressures from about 1 to 3.2 psf resulted in damage claims predominantly for glass on the order of one per 100,000 population per flight, with about one in three being judged valid. Such claims-per-exposure statistics, while useful as rules of thumb, cannot begin to adequately reflect the structural variables needed to predict response in new situations.

2. Flight test series in Oklahoma City, Chicago, and St. Louis resulted in over 10^9 boom-person exposures. The associated property damage resulted in paid-out claims averaging about $220 per million boom-person exposures. On the average, frequency of paid claims for glass damage far exceeded that for plaster damage.

3. Prestressing, stress concentrations, and faulty material often found in structures are considered to account for part of the difference between the results of the monitored experiments and the unmonitored experiments. Another part of the difference is attributed to random modifications of the booms due to atmospheric effects. The remainder is considered to arise from the prior history of the unmonitored structures. Visible damage from a sonic boom, when it occurs, will depend in part on how much of the lifetime of the structure has already been consumed.

Chapter 6 briefly summarizes the results of various studies that have been conducted concerning the seismic effects of sonic booms and the possibility of avalanches being triggered by sonic booms. The following are the main conclusions reached as a result of this review:

1. The motion of the ground due to sonic boom excitation is of relatively small amplitude. The fact that measurable ground motions exist taken together with the explosive character of air loading suggests that avalanches might be triggered by sonic booms incident on unstable snow accumulations; up to now, however, no direct evidence of cause and effect is available. From a scientific point of view, there are and will continue to be a large number of unstable terrain features that could be affected by the sonic boom differently depending upon their degree of instability or particular structural status.

2. The cited test series in which sonic booms failed to trigger snow avalanches were carried out under "low" avalanche hazard conditions. Furthermore, the differences between triggering snow and earth avalanches needs to be better understood.

These two chapters do a good job of summarizing the state of knowledge as of 1970 concerning the response of structures to sonic booms and sonic boom effects on terrain.

SP-68
...IC BOOM ANALOGUES FOR INVESTIGATING INDOOR WAVES AND STRUCTURAL RESPONSE
Sui Lin
UTIAS Technical Note No. 158, Nov. 1970

This paper presents a method of investigating the amplitude of the indoor pressure wave induced by a sonic boom for the case of a partly open window. This is of interest since previous experimental results indicated that the maximum amplitude of the indoor wave is larger than the maximum amplitude of the incident sonic boom. The method used in this investigation is an electrical analogue.

The problem considered is a room in a large building. Its front wall with an open window is exposed to sonic booms. On the other side of the room there is a closed window. To simplify the problem it is assumed that the rear closed window is the only structural member which will be excited by the sonic boom. It is also assumed that the low frequency components of the sonic boom, which contain most of the acoustical energy, dominate the indoor acoustical wave and the structural dynamic response, and that their wave lengths are much larger than the dimension of the room.

The mechanical vibrating member, the rear closed window, is represented by a spring-mass-damper system. The acoustical system and the simple mechanical vibrating system are then described by two differential equations. The mechanical vibrating system is then transformed into an acoustical system to get a combined acoustical system. The equation describing this acoustical system is shown to be analogous to that describing an electrical circuit. Using this analogy, an electrical analogue of the acoustical system is developed. The advantages given of using an electrical analogue to simulate an indoor acoustical wave and the structural dynamic response induced by a sonic boom are as follows:

(1) the electrical model is easy to set up; (2) the variables being investigated can easily be varied over a wide range; (3) the space used for the electrical equipment is very small; (4) the voltage and the current of the electrical circuit can be easily measured with simple equipment; (5) the time per test is extremely short; and (6) the cost per test is very low.

The experimental results of acoustical response obtained using the electrical analogue showed good agreement with those of Vaidya (see capsule summaries SR-72 and SR-73), indicating that the electrical analogue is a suitable device for investigating the room response to sonic booms. Based on the assumption that the low-frequency components of the sonic boom dominate the indoor acoustical wave, this analogue method is expected to be more accurate for booms of larger duration or for rooms with smaller dimensions.

SR-69
NORMAL SHOCK WAVE REFLECTION ON DEFORMABLE SOLID WALLS
R. Monti
Meccania, Dec. 1970, pp. 285-296

In this paper the problem of the reflection of a normal shock wave impinging on a deformable solid wall is examined. Both the theoretical and experimental aspects of the problem are covered.

After a brief review of the formulae governing the shock wave propagation in a continuous medium, the particular case of a shock wave propagating in a perfect, constant heat capacity gas and reflecting on an elastically perfect solid is examined and solved. The problem is reduced to the solution of a third degree algebraic equation which is solved in terms of the reflected shock Mach number as a function of: (1) the number of degrees of freedom of the gas molecule (monotomic, diatomic, etc.); (2) the incident shock wave strength; and (3) a single deformation parameter which accounts for the gas initial conditions, for the elastic characteristics and the initial conditions of the Hookian solid. Some numerical examples are presented in which the solid material of a finite thickness, is supported by a rigid wall. During the interaction between the shock and the solid it is shown that overpressures larger than the ones which would be obtained for a shock reflection on a rigid surface can be reached.

The second part of the work presents the experimental data, obtained by means of a shock tube, on normal shock reflection from particularly soft and light materials (expanded foams). The numerical results are in good agreement with the experimental results, after a correction, was made to account for some peculiar experimental conditions.

SR-70
TRANSMISSION OF SONIC BOOM PRESSURE THROUGH A WINDOW PANE
J. E. Benveniste and D. H. Cheng
NASA CR-111846, 1970

In this paper the pressure transmitted through a square window for a normal N-wave is computed under the assumption that the window is set in a rigid baffle. The window is assumed square and simply supported along its edges.

Starting with the equation of motion for a simply supported plate, the following simple approximate formula is derived which can be used (it is stated) in most cases commonly encountered in practice:

$$2\,P_{int} = \frac{2}{\pi}\,\frac{\rho_a}{\rho_g}\,\frac{L}{h}\,q(o)$$

where P_{int} = interior pressure

ρ_a = density of air

ρ_g = density of plate material

L = side of square plate

h = plate thickness

and $q(t) = P_{ext} - P_{int}$,

where P_{ext} = exterior pressure, and

t = time measured from instant of incidence.

This equation is used to show that for usual dimensions the pressure transmitted has small magnitude (about 0.035 q(o)).

It is shown that the computed transmitted pressures are much less than the internal pressure measured in frame houses during sonic boom experiments. It was believed by the authors that the discrepancy is due to transmission of pressure through the areas of wall and roof as well as windows.

For a discussion of the transmission of sonic booms through open windows, see capsule summaries SR-68, SR-72, SR-73.

SR-71
EXPLOSIVELY GENERATED AIR PRESSURE WAVES FOR STRUCTURAL FORCING
M. J. Harper, S. J. Hawkins, J. A. Hicks
Journal of Sound & Vibration, Vol. II, No. 2, 1970, pp. 217-224

This paper is essentially the same as an earlier paper by Hawkins and Hicks (see capsule summary SM-2). It does, however, treat in much greater depth than the earlier paper the theory of spherically symmetric explosions and highly asymmetric explosions. The reader is referred to the capsule summary of the earlier paper for a discussion of the simulation technique.

SR-72
THE TRANSMISSION OF SONIC BOOM SIGNALS INTO ROOMS THROUGH OPEN WINDOWS; PART I: THE STEADY STATE SOLUTION
P. G. Vaidya
NASA CR-11 1786, 1970

In this paper, as a first step in calculating transient pressure time-histories in rooms due to sonic booms, a solution is derived for the pressure field generated inside a room due to an incoming harmonic wave, incident on an open window. The basic problems of sound radiation and diffraction, related to this problem, are first discussed. These are made use of to obtain a solution in the case of a room with hard walls and normal incidence, first by viewing the room as a terminated duct and later by the Green's function method. The solution consists of an equation describing the sound field inside the room. Detailed calculations illustrating various representative cases are presented in part II of this report (see capsule summary SR-73).

SR-73
THE TRANSMISSION OF SONIC BOOM SIGNALS INTO ROOMS THROUGH OPEN WINDOWS: PART II: THE TIME DOMAIN SOLUTIONS
P. G. Vaidya
NASA CR-111787, 1970.

In this report, the time domain extensions of results derived in Part I (see capsule summary SR-72) are obtained. Expressions for pressure fields inside a room with an open window due to a delta impulse type excitation are obtained, both by using a normal mode type approach and a Helmholtz resonator analogy. It is shown that both methods can be used together to give the complete response to a general transient excitation of the room and that each method has its own advantages and disadvantages.

SR-74
U. K. RESEARCH IN SONIC BOOM
J. B. Large and D. N. May
Society of Automotive Engineers, February 8, 1971, pp. 5-8

This paper reviews research work in the United Kingdom on the objective effects of the sonic boom on humans and structures, and the subjective response of humans. Only the portion of the review dealing with structural response will be summarized here. For a summary of the review of human response studies, the reader is referred to capsule summary HRSC-63.

The studies reviewed include those by Vaidya (see capsule summaries SR-72 and SR-73), Popplewell (see capsule summary SR-58), and Craggs (see capsule summaries SR-45 and SR-48). Several other less significant investigations are also mentioned.

The review presented in this paper is very brief, and the aforementioned subjects are not discussed in any depth.

SR-75
STRUCTURAL RESPONSE TO SONIC BOOMS
Roland L. Sharpe and Garrison Kost
Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, April 1971, pp. 1157-1174

This paper presents a summary of the state of knowledge concerning structural response to sonic booms as of 1971. Included in the summary are: (1) results of the Oklahoma City sonic boom tests (see capsule summary SR-12); (2) results of the White Sands sonic boom tests (see capsule summary SR-16); (3) results of the Edwards Air Force base sonic boom tests (see capsule summary SR-39); and (4) analytical methods of determining structural response to sonic booms (see capsule summaries SR-28, SR-40, SR-41, SR-53, and SR-57, for example).

The following conclusions were reached as a result of this look into the state of knowledge of sonic boom structural response theory:

1. Field test experience has indicated that properly designed and constructed houses should not be damaged by low overpressure sonic booms. However, the large number of claims filed and the results of damage claim investigations indicate that sonic booms with nominal peak overpressures of 2 psf to 3 psf can cause minor damage.

2. The average cost per sonic boom incident is quite low. However, there have been a few cases where large glass store fronts were broken or other substantial damage was incurred.

3. Experience to date indicates that a large percentage (55% to 80%) of all damage incidents will be glass damage.

4. Because there was a pretest glass pane condition survey at Edwards AFB, the number of panes damaged by test missions should be an indicator of glass damage to be expected from future supersonic flights generating sonic boom overpressures on the order of 2 to 3 psf. The rate was one damaged pane per 7,900,000 boom-pane exposures.

5. Plate and racking deflections in typical houses from sonic booms with 1 psf to 2 psf overpressure are small and on the order of 0.034 in. and 0.005 in. respectively.

6. Sonic booms from large aircraft affect a larger range of structure elements than those from smaller aircraft.

7. The response to sonic booms can be adequately predicted if the characteristics of the boom and structure elements are known.

8. Free field signatures can be used to adequately predict structural response.

9. Structure response prediction can be greatly simplified by use of a boom pressure wave model.

This is an excellent summary of structural response to sonic booms.

SR-76
MEASUREMENT OF THE NATURAL FREQUENCIES OF THE WALLS OF BUILDINGS SENSITIVE TO SONIC BOOM
P. De Tricaud
Royal Aircraft Establishment, Library Translation No. 1589, May 1971

This paper describes a method of measuring the dynamic characteristics and natural frequencies of internal dividing walls and of window areas which might be susceptible to damage from sonic booms. The method consisted of setting the partition in motion by the impact (at its center) of a tennis ball thrown by hand and caught again before it touched the ground, in such a way as to avoid all disturbance of the signal. An accelerometer was fixed, by means of double sided adhesive tape, to the center of the face of the partition on the opposite side to that which received the tennis ball. Preliminary tests showed that this method of fixation could be used with an error of $\pm$ 0.5 dB between 20 and 3000 Hz. The output of the accelerometer was then analyzed to determine the natural frequency.

The following results were found for the first natural frequency (F11) of various structural elements:

f_{11} = 17.5 Hz for window panes

f_{11} = 21.9 Hz for partitions made of solid plaster slabs.

f_{11} = 25.1 Hz for partitions made of gypsum bricks

f_{11} = 47.6 Hz for "Placopan" partitions.

It is shown that the results from the same type of dividing wall can vary by a large factor depending on how the material from which the wall is made is manufactured and on how the interior wall is attached to the main structure.

The measured results are compared with those calculated for various types of internal walls and show a reasonable degree of agreement between calculated and measured values provided that the physical constants of the materials are known with some accuracy.

SR-77
MODEL STUDIES OF HELMHOLTZ RESONANCES IN ROOMS WITH WINDOWS AND DOORWAYS
Gary Koopmann and Howard Pollard
NASA CR-1777, June 1971

The cavity resonance of a room enclosed by large windows and open doors can be set into motion if the windows should suddenly be subjected to an impulsive load, such as a sonic boom. This paper presents the results of a study conducted to determine the conditions and possible damaging consequences of such a resonance.

The study utilized the method of expressing the windows, air, and common doorway of two typically joined rooms in terms of equivalent lumped elements. The resultant dynamic system was treated as a series of coupled Helmholtz resonators and had as its mathematical description a set of coupled, second order differential equations. Solutions to these equations were generated on an analog computer for several types of impulsive loading conditions. Experiments were also performed on actual scale models to guide the computer study.

The following conclusions were reached as a result of this study.

1. In connected rooms which are enclosed by large windows, motion of the windows in their fundamental modes influences and is influenced by the Helmholtz resonances of the rooms.

2. Mathematical descriptions of such systems which utilize equivalent lumped element representations produce response data which closely resemble those obtained from experiments performed on physical models.

3. A coincidence of frequencies between the window and room cavity resonance produced no increase in the maximum response of the window for a given loading. However, the room pressure reached a maximum which was 3.2 times higher than that corresponding to the case where the two frequencies differed by a factor of 4.

4. When two similar, large windows share the same room, the motion of one can cause the other to respond with nearly the same maximum amplitude.

5. With two similar, large windows located in different rooms joined by a common doorway, the initiation of the Helmholtz room resonance by motion of the window in one room can cause the window in the adjoining room to respond at nearly the same maximum amplitude.

This is the most extensive investigation that has been conducted concerning the effects of Helmholtz resonance on the response of windows and indoor pressure to sonic booms.

SR-78
PENETRATION OF SONIC BOOM ENERGY INTO THE OCEAN: AN EXPERIMENTAL SIMULATION
J. F. Waters
Noise & Vibration Control Engineering, Proceedings of the Purdue Noise Control Conference, Lafayette, Indiana, July 14-16, 1971, pp. 554-557

This is a condensed version of an earlier report by Waters and Glass (see capsule summary SR-66). The reader is referred to the capsule summary of that report for details of this work.

SR-79
THE VIBRATION OF A BOX-TYPE STRUCTURE II. RESPONSE TO A TRAVELLING PRESSURE WAVE
N. Popplewell
Journal of Sound and Vibration, Vol. 18, No. 4, October 1971, pp. 521-531

In this paper a finite element method is formulated for determining the transient response of a box-type structure to a travelling, arbitrarily shaped pressure wave, such as a sonic boom. In this method the structure is represented by a number of rectangular elements with four unknown displacements per nodal point. The vibration of a single point of a three-dimensional surface generally has components both normal and tangential to the surface. However, the present simplified analysis neglects the tangential components, since for many practical structures the tangential components are negligible. It is assumed that the pressure over any one finite element is uniform in a given time interval.

The standard equation of motion with no damping is obtained by using the Euler-Lagrange equation for each element. The resulting equation is then solved using a standard fourth order Runge-Kulta procedure. The results give the acceleration, velocity, and displacement at chosen points of the structure.

In order to check the theoretical results, an experiment was performed using a conical shock tube to determine the response of a simple, yet realistic box configuration. Similarity considerations were used to ensure that the behavior of the model was representative of a full-scale, single story structure.

A comparison of theoretical and experimental results showed that satisfactory overall agreement was obtained by using only four elements per face and a simple representation of the pressure-time history over the box. This representation consisted of a pressure doubling on the wall normal to the incident wave and a pressure variation the same as the free field on all other walls and on the roof. The greatest discrepancy between experimental and theoretical results occurred on the back face due to an initial racking motion (not considered in the model) and an inadequate theoretical description of the loading on this face. Assumptions regarding the loadings on the other faces were found to be fairly realistic.

This paper is a modified version of Popplewell's Ph.D. thesis (see capsule summary SR-58).

SR-80
EFFECT OF SONIC BOOM ON STRUCTURES; THIRD REPORT: MEASUREMENT OF EIGENFREQUENCIES OF BUILDING STRUCTURES WHICH ARE SENSITIVE TO THE "BOOM"
P. De Tricaud
NASA TT F-14,057, Nov. 1971

Another translation of this same paper was made by the Royal Aircraft Establishment. That translation is summarized in capsule summary SR-76. The reader is referred to that capsule summary for details of this work.

SR-81
EFFECT OF SONIC BOOM ON BUILDINGS (SECOND REPORT: ELABORATION OF A METHOD FOR CALCULATING THE DEFORMATION OF CONSTRUCTIONS)
Anonymous
NASA-TT-F-14056, December 1971

This report consists of two parts. The first part presents a calculation of the acoustic response of various room configurations in buildings to sonic booms. The second part is concerned with vibrations which are produced in interior partitions, ceilings, and window panes as a result of sonic booms.

In the calculation of acoustic response, the configurations studied include single rooms having openings in walls, penetration of booms through flexible walls, two rooms coupled acoustically by openings, and rooms with window panes. The study shows that the system consisting of a room and an opening can be considered as a Helmholtz resonator for the study of the penetration of a sonic boom. Consequently, the pressure signature in the interior of the room will have the shape of a damped sinusoid. Its maximum will be equal to twice the overpressur of the incident sonic boom crest. This overpressure is measured on the facade and is more than two times the overpressure measured on the ground. This is true when the signature interval of the sonic boom is approximately equal to the period corresponding to the eigenfrequency of the system consisting of the room and the opening. The hypotheses made do not make it possible to predict the rise time of the internal overpressure. In order to obtain resonance with a supersonic fighter, an eigen-frequency of about 10 Hz is required, which is commonly found. With a supersonic transport of the Concorde type, an eigen-frequency of 3 Hz is required, which is only obtained for a very small opening with respect to the room. On the other hand, a double resonator (two rooms connected by an open door and the sonic boom penetrates into one of them through an opening) can have an eigenfrequency of this order. In addition, the overpressures obtained can be considerably higher.

The second part of the report investigates the vibrations produced by sonic booms in interior partitions, ceiling, and window panes by calculating the vibrations of a homogeneous rectangular plate. These vibrations were determined using the classical theory of dynamic deformation of a plate. It is assumed that the membrane stresses can be ignored and that there are no internal prestresses.

Helmholtz resonance was also discussed in a report by Koopman and Pollard (see capsule summary SR-77). That study also showed that Helmholtz resonance can lead to much higher indoor overpressures than would normally be experienced.

SR-82
THE EFFECTS OF SONIC BOOM AND SIMILAR IMPULSIVE NOISE ON STRUCTURES
Prepared by National Bureau of Standards
Environmental Protection Agency Report No. NTID 300.12, December 31, 1971

This report presents a summary of the results of previous experimental investigations (see capsule summaries SR-12, SR-16, SR-20, SR-23, SR-44, and SR-39 for example) concerning the effects of sonic booms on structures and terrain features.

The following are some of the conclusions reached as a result of this survey of previous investigations:

1. In general, there has been little sonic boom damage resulting from laboratory and controlled overflight experiments with monitored structures from peak pressures up to 20 psf; there was some extension of plaster and paint cracks, however. Controlled overflights with unmonitored structures subjected to a range of nominal peak overpressure from about 1 psf to 3.2 psf resulted in damage claims, predominantly for glass, of the order of one per 100,000 population per flight; i.e. 100,000 boom-person exposures, with about one in three being judged valid. Such claims per exposure statistics, while useful as rules of thumb, cannot begin to adequately reflect the structural variables needed to predict response in new situations.

2. Ground response to sonic booms varies somewhat depending on the type of soil involved, but a general result of the studies was that induced particle velocities of about 50 to 500 microns/sec were associated with nominal peak pressures of 0.5 to 5.0 psf. This compares to a value of about 150 microns per second which is associated with the footsteps of a 200 lb man. The effective areas covered on the ground are, of course, very different; the boom-induced motions are correlated over distances of the order of miles, whereas footstep-induced motions decay within tens of feet.

3. The fact that measurable ground motions exist, taken together with the explosive character of air loading, suggests that avalanches might be triggered by sonic booms incident on unstable snow conditions; however, no direct evidence of cause and effect is available.

Sharpe and Kost (see capsule summary SR-75) also summarized the state of knowledge as of 1971 concerning the effects of sonic-booms on structures. They treated both theoretical and experimental results, however, while the present paper deals almost exclusively with experimental results.

SR-83
REFLECTIONS OF WEAK SHOCK WAVES FROM ACOUSTIC MATERIALS
M. Cloutier, F. Devereux, P. Doyon, A. Fitchett, D. Beckman, L. Moir and L. Tardif
Journal of the Acoustical Society of America, Vol. 50, No. 5 (Part 2) 1971, pp. 1392-1393

In the investigation discussed in this short note a number of materials having good acoustic absorption properties were tested in order to determine their relative effectiveness in attenuating weak high-frequency shock waves propagating in atmospheric air. Weak shock waves with an N-wave configuration of about 110 μsec duration were generated by rifle bullets travelling at 2400 ft/sec over samples of acoustic material supported on a metal plate. Details of the reflection of these waves at the surface of the various materials were monitored by using shadow-graph-schlieren photographic techniques and pressure transducers. The urethane materials gave a high amount of surface reflection compared to fiberglass materials of similar density. The least surface reflection was obtained with very low density (less than 1.0 lb/ft^3) fiberglass.

SR-84
AN IMPROVED METHOD FOR ASSIGNING A DYNAMIC MAGNIFICATION FACTOR TO N-WAVES
G. Koopmann, R. M. Orris
Journal of Sound and Vibration, Vol. 19, No. 3, 1971, pp. 373-377

This brief note presents an improved method of assigning a dynamic magnification factor to N-waves. The dynamic magnification factor (DMF) is defined as the ratio of the maximum dynamic displacement of the structural element of interest to the displacement that would occur under a static load equal to some quantity typifying the N-wave. The DMF is expressed as a function of the non-dimensionalized product of the natural frequency of the system f, and a typical time period of the N-wave. If the quantity chosen to normalize the maximum displacement is a satisfactory measure of the dynamic effects of the sonic boom, it is stated that there should be a significant amount of grouping between the DMF's found for different N-waves.

Since choosing a normalizing quantity is a somewhat arbitrary process, various authors have done it in different ways. Some have used the peak overpressure, while others have used an effective overpressure defined by $\Delta P = 4I/T$, where I is the positive impulse and T is the signature interval. The present paper suggests the use of a redefined effective overpressure as the normalizing quantity in order to get more consistent results for distorted sonic boom waveforms. The modification suggested is that the value used for I in the definition of effective overpressure should be an average of the positive and negative impulses of the N wave, i.e.

$$I' = (I_{max} - I_{min}).$$

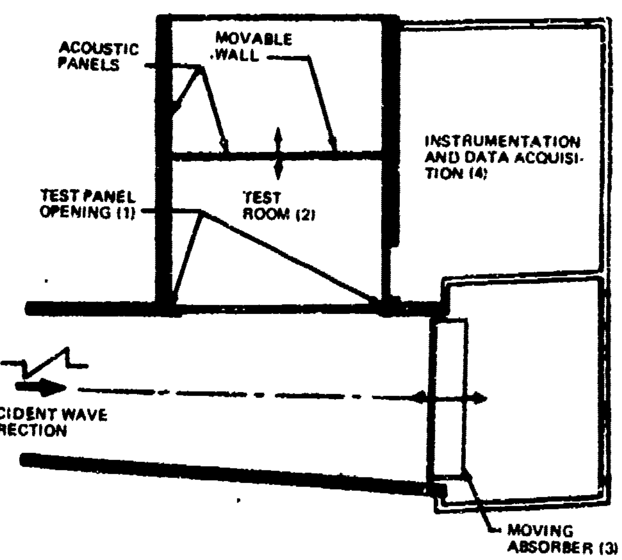
I_{min} is the minimum value of the running integral of the overpressure with respect to time, taken over the total duration of the N-wave, and I_{max} is the maximum value of this integral in the same time range. The effective overpressure then becomes $\Delta P = 4I'/T$.

It is shown that the grouping found between the results for different N-waves when the normalizing quantity is the redefined effective overpressure is better than that found using either the peak overpressure or the effective overpressure as the normalizing quantity.

SR-85
EXPERIMENTAL DETERMINATION OF ACOUSTIC AND STRUCTURAL BEHAVIOR OF WALL PANEL - CAVITY CONFIGURATIONS EXPOSED TO SONIC BOOMS
W. Peschke, E. Sanlorenzo, M. Abele
NASA CR-111925, 1971

An experimental program is described in this report which was performed to investigate the structural response and acoustic transmission characteristics of a 6.25 ft x 10.42 ft, 1/4-inch thick glass pane and two 8 ft x 12 ft standard wood frame construction wall panels acted upon by a sonic boom N-wave. The specific objectives of the program were: (1) to determine the behavior of several wall panels with regard to their structural response and acoustic transmission characteristics; (2) to provide data describing the acoustic properties of a variable-volume cavity (test room) in conjunction with the test panels; and (3) to record and evaluate the damage to test panels induced by repetitive sonic boom application.

The experiment was performed using the NASA-GASL sonic boom simulator (see capsule summary SM-9). The figure below shows the basic test configuration. It is important to note that in all cases the windows and test panels were parallel to the direction of N-wave propagation. A typical test series included variation of the N-wave duration to assess the wall cavity behavior as a function of the period of the disturbance for several cavity depths. In testing involving the glass pane, this permitted an assessment of the influence of a variation in acoustical stiffness imposed by room volume change, N-wave duration was varied to determine at which wavelength(s) one would observe significant effects in the panel-room interaction. In all cases, the range of interest was found to be between 30 and 130 ms, although preliminary testing was performed over a range extending from 20 to 200 ms. Testing over a range of incident wave overpressures was also performed. In addition to wave overpressure, the panel acceleration, induced strains, and cavity pressure were recorded.



Test section of the sonic boom simulator

The latter part of the program involved repetitive applications of the sonic boom wave to the wall panels discussed above. Specifically, each of the two panels were exposed to 500 tests at each of three overpressures to investigate the likelihood and extent of failure due to cracking of the interior plaster surface of the panel. Resulting cracks in the plaster which were not visible under ordinary light were made visible using ultraviolet light. It was found that, for both panels, a significant number of cracks were concentrated at one edge of the panel. In each case, the high density of cracks corresponded to the location of a minimum stud spacing.

The following conclusions were reached as a result of this investigation:

1. The results indicate that the initial glass pane acceleration and cavity pressure amplitude are essentially independent of the N-wave duration. Although the initial acceleration of the pane is practically constant as the cavity volume increases, the initial pressure is directly proportional to the variation in stiffness ratio.

2. The N-wave duration which induces maximum dynamic and acoustic effects in the glass pane and cavity is approximately 60 ms., and the dominant modes excited in the glass pane correspond to frequencies of 7, 10, 14, and 40 Hz.

3. The maximum multimodal dynamic amplification factor (DAF-defined as the ratio of maximum dynamic response to static response under equal loading conditions) measured in terms of strain in the center of the glass pane is approximately 0.5.

4. Maximum acoustic effects in the cavity are induced for the plaster wall panels at N-wave durations of 60-80 ms (panel with window) and 75 ms (panel without window).

5. The results of tests involving repetitive application of the sonic boom to the wood frame (plaster interior) wall panels indicate that cracking of the plaster surface can occur at incident wave overpressures on the order of 1 psf. The failure of the plaster is progressive and crack propagation has been observed at overpressures below 2 psf.

The last conclusion contradicts the findings of the White Sands sonic boom tests (see capsule summary SR-16). In one portion of the study, 680 successive flights at an overpressure of 5 psf were found to produce no cumulative damage effects. However, the wall damage inspection procedures apparently suffered from an inability to detect extremely fine cracks in plaster walls, while the procedure used in the present investigation made detection of such cracks possible.

SR-86
SONIC-BOOM ANALOG FOR INVESTIGATING INDOOR ACOUSTICAL WAVES
Sui Lin
Journal of the Acoustical Society of America, Vol. 49, No. 5 (Part I) 1971, pp. 1386-1392

This is a condensation of an earlier report by Lin (see capsule summary SR-68). The reader is referred to the capsule summary of that paper for details of this work.

SR-87
SONIC-BOOM-INDUCED BUILDING STRUCTURE RESPONSES INCLUDING DAMAGE
Brian L. Clarkson and William H. Mayes
The Journal of Acoustical Society of America, Vol. 51, No. 2 (Part 3), Sonic Boom Symposium, February 1972, pp. 742-757

This paper describes and summarizes the theoretical and experimental studies of the response of structures to transient pressures. The topics covered in this review are:

1. Theoretical studies: (a) response of simple structural elements to transient pressures; (b) multi-degree-of-freedom linear model; (c) effects of nonlinearities; (d) windows rattling; (e) effect of a backing cavity; (f) coupled resonators; and (g) three-dimensional effects.

2. Overflight studies of building structures and structural elements: (a) building overall dynamic responses; (b) wall accelerations; (c) wall and window displacements; (d) stress response; and (e) historic buildings.

3. Damage to house structures: (a) window damage; (b) plaster damage; (c) damage claims; and (d) damage prediction.

The studies upon which the review of these various topics is based include those made by Cheng and Benveniste (see capsule summary SR-53), Crocker and Hudson (see capsule summary SR-57), Craggs (see capsule summary SR-45), Pretlove (see capsule summary SR-94), Lowery (see capsule summary SR-47), Koopman and Pollard (see capsule summary SR-77), Popplewell (see capsule summary SR-79), Hawkins and Hicks (see capsule summary SM-2), Blume, et al (see capsule summaries SR-16 and SR-39), Power (see capsule summary SR-10), and Wiggins (see capsule summary SR-35).

This is a very good summary of the state of knowledge concerning structural effects on sonic booms as of 1971.

SR-88
SEISMIC AND UNDERWATER RESPONSES TO SONIC BOOM
J. C. Cook and T. Goforth
The Journal of the Acoustical Society of America, Vol. 51, No. 2 (Part 3), Sonic Boom Symposium, February 1972, pp. 729-741

The purpose of this paper is to review and summarize several studies made since 1965 on the seismic and underwater effects of sonic booms. Both theoretical and experimental studies are included.

The review of underwater sonic boom effects is based upon the studies made by Cook (see capsule summary SR-63), Sawyers (see capsule summary SR-51), Young (see capsule summary SR-44), and Waters and Glass (see capsule summary SR-66). From this review the following conclusions are reached in this paper:

1. The pressure waveform underwater near the surface is almost identical to that of the N-wave in air. However, it is rapidly smoothed and attenuated with depth. It typically becomes about one-tenth as large at a depth less than 0.6 of the wavelength of the N-wave.

2. Overpressures may exceed pressures due to background noise by factors of up to 100 at moderate depths for frequencies between 2 Hz and 100 Hz. However, these levels are less than 0.16% of pressures known to harm marine life in single exposures.

3. Adequate quantitative theories for the underwater effects of sonic booms have been developed. These have been verified by scale-model experiments.

The review of seismic effects is based largely upon an earlier report by Goforth and McDonald (see capsule summary SR-50). The seismic effects of sonic booms are summarized as follows:

1. There are two major effects: the "static" deformation field traveling with the surface load, and air-coupled Rayleigh wavetrains following each N-wave. The latter have frequencies and amplitudes determined by the aircraft speed and the geology. The static deformation has always been the largest effect in over 1000 seismograms recorded in field tests. Its amplitude is proportional to the peak overpressure of the sonic boom.

2. The maximum ground motion recorded was about 100 times the largest natural, steady seismic noise background. However, this was still less than 1% of the accepted seismic damage threshold for residential structures.

3. Movement decreases rapidly with depth and is less for hard rock than for soft ground.

4. Quantitative theories for the major seismic effects agree reasonably well with experimental results.

5. Seismic forerunner waves, which begin at least 7 sec before arrival of the sonic boom, might be exploited for automatic warnings to lessen the startle effect of sonic booms.

6. Sonic booms probably cannot trigger earthquakes, but might possibly precipitate incipient landslides or avalanches in exceptional areas which are already stressed to within a few percent of instability.

This is an excellent summary of the state of knowledge as of 1970 concerning the seismic and underwater effects of sonic booms.

SR-89
SONIC BOOM EXPOSURE EFFECTS II.1: STRUCTURES AND TERRAIN
G. Weber
Journal of Sound and Vibration, Vol. 20, February 22, 1972, pp. 505-509

This paper presents a very general review of the effects of sonic booms on topographical features and structures. The following are some of the main points of the review:

1. The results obtained in ground motion experiments in the United Kingdom show that the levels of vibrations due to sonic booms - peak particle velocities up to about 300 μm/s - are usually of the same order as those associated with the passage of vehicles. Their effects on structures would thus not be sufficient to cause damage. These results confirm those of McDonald and Goforth (see capsule summary SR-50).

2. It has been shown that under water an N-wave is rapidly smoothed and attenuated with depth, and is reduced to about 0.1 of its surface amplitude at a depth of a few meters.

3. The effect of ground motion on surface topographical features is the same as that for structures.

4. Generally, the effects of sonic booms on structural elements over and above that which occurs naturally in and around houses due to other environmental factors are small. Hence, damage to primary structures of dwellings even under extreme assumptions is not to be expected.

5. If the loading functions - the effective boom characteristics - and the size, mass, damping, and stiffness of a structure are known, the maximum structural response achieved during the dynamic loading period, or effective static load can be derived.

6. Damage criteria can only be used statistically to predict the likelihood of damage on a large group of buildings.

A much more complete and extensive review of sonic boom structural effects was made in an earlier paper by Clarkson and Mayes (see capsule summary SR-87). Also, for a more extensive review of seismic effects than is given in the present paper see the paper summarized in capsule summary SR-88.

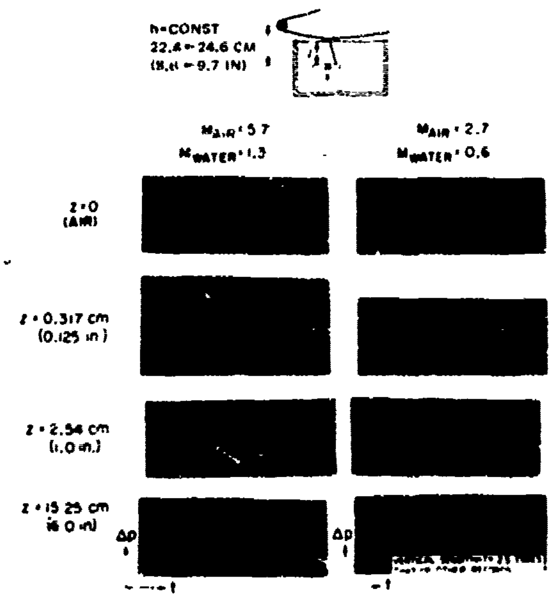
SR-90
STUDY OF THE SENSITIVITY OF NITROGLYCERIN TO WEAK SHOCK WAVES (SUPERSONIC AIRCRAFT BANGS) [UNTERSUCHUNG DER EMPFINDLICHKEIT VON NITROGLYCERIN GEGEN SCHWACHE STOSSWELLEN (FLUGZEUGKNALL)]
H. W. Koch, I. Bischoff, and L. Philipp
N73-16658, Institut Franco-Allemand de Recherches, St. Louis, France, ISL-14/72, April 1972 (In German)

In this experiment a sonic boom generator was used to produce shock waves having overpressures up to about 100 psf and durations of 345 ms. The purpose of the experiment was to investigate the resistance of nitroglycerin to weak shock waves corresponding to the sonic boom caused by aircraft. Nitroglycerin samples 6 mm thick were placed in a bowl covered with a thin plastic layer and exposed to the simulated sonic booms. It was found that no detonations occurred either during these tests or during the same tests carried out with other primers.

This was the first experiment to demonstrate that even very strong sonic booms should not pose any hazard in regard to the accidental detonation of explosives.

SR-91
BALLISTIC RANGE INVESTIGATION OF SONIC-BOOM OVERPRESSURES IN WATER
G. N. Malcolm and P. F. Intrieri
AIAA Paper No. 72-653, Presented at AIAA 5th Fluid and Plasma Dynamics Conference, Boston, Mass., June 26-28, 1972

The results of an investigation of sonic boom overpressures in water are presented in this paper. Ballistic range tests were made in the Ames Research Center Pressurized Ballistic range by gun-launching small cone-cylinder mo els over water. Tests were conducted at Mach numbers of 2.7 and 5.7, in air, corresponding to Mach numbers of 0.6 and 1.3, respectively, in water. The results of these experiments consisted of two types of data -- shadowgraph pictures and underwater pressure measurements. The figure below, which was taken from this paper shows a sample of the data obtained.



Sample oscilloscope records of pressure measurements in air and underwater

The results of this experiment led to the following conclusions:

1. Aircraft flights over water that produce an incident shock wave which travels along the water's surface at speeds greater than the speed of sound in water ($M_{air}>4.4$) will produce a shock wave in the water; if the speed of the incident wave is less than M = 4, only sound waves will be produced underwater.

2. The peak pressure associated with the underwater shock wave attenuates very little with depth.

3. The peak pressure of the underwater sound wave decays rapidly with water depth and is well predicted by theory (see capsule summary SR-51).

This experiment was an excellent verification of Sawyers' theory.

SR-92
ADDITIONAL SONIC BOOM DATA RELATED TO TESTS CONDUCTED AT WHITE SANDS, NEW MEXICO, AND EDWARDS AIR FORCE BASE
Lloyd A. Lee
Federal Aviation Administraton Report No. FAA-RD-72-114, September 1972

This report presents a tabulation of previously unpublished data which were compiled in the form of notes and recordings during the sonic boom experiments conducted in 1964-1965 at the White Sands Missile Range, New Mexico, and in 1966 at Edwards Air Force Base, California. Strain gage readings are tabulated and correlated with overpressure measurements, aircraft Mach number, altitude and directional vector from the White Sands tests and window sizes and strain gage locations in test structures associated with the Edwards Air Force Base program. For further details of the tests conducted at White Sands and Edwards Air Force Base, see capsule summaries SR-16 and SR-39, respectively.

SR-93
VIBRATIONS OF CIRCULAR ELASTIC PLATES DUE TO SONIC BOOM
L. J. Pavagadhi and M. D. Yajnik
Journal of the Acoustical Society of America, Vol. 52, No. 1 (Part 2) 1972, pp. 260-269

The problem of axisymmetric transient vibrations of large circular plates due to sonic booms is considered in this paper. The effects of transverse shear, rotating inertia, and the external and internal dampings are neglected. The equation of motion for a circular elastic plate, including the term for a sonic boom N-wave, is solved by using the modified finite Hankel transform, the Laplace transform, and a digital computer.

The results, showing various modes of vibrations of plate made from three different materials (concrete, mild steel, and aluminum), are plotted for the boom duration, using a digital computer. The time displacement history of the center of the plate indicates that the center of the plate not only produces the largest dynamic deflection but also tends to build up with time and has a relative maximum in each half period of the sonic boom. The results also indicate that the dynamic deflection of the center of the plate increases approximately up to two-thirds of the half-boom period. It is concluded from these results that an increase in boom period will result in increased dynamic deflection.

It is shown that the effect of overpressure is similar to a static loading on the plate. Thus an increase in the overpressure of the sonic boom will increase the dynamic amplitude of the plate but without any additional dynamic amplification if the boom period remains the same. It is concluded that for a normal flight the boom duration has a more significant effect on the vibration of the plate than the overpressure does.

In an earlier paper (see capsule summary SR-57) Crocker and Hudson, using a simple spring mass system and the sonic boom as the forcing function, reached a similar conclusion regarding the effect of sonic boom duration on structural response. This conclusion remains to be verified experimentally, but, if shown to be correct, it will mean that controlling structural response to sonic booms will require the sonic boom period to be controlled.

SR-94
AN ESTIMATE OF SONIC BOOM DAMAGE TO LARGE WINDOWS
A. J. Pretlove and J. F. Bowler
Journal of Sound and Vibration, Vol. 22, No. 1, 1972, pp. 107-112

In this paper a preliminary estimate, based on statistical data, is made of the likelihood of damage to large windows due to sonic booms. The study was confined to windows having each dimension greater than six feet. Since statistical data on the dynamic properties of large windows were not available elsewhere, a survey was made of the dynamic characteristics of over 300 large windows in the Reading area of England. This survey produced the data required to calculate the response of a typical window. For each of the 308 windows, a dynamic magnification was evaluated using the work of Crocker and Hudson (see capsule summary SR-57), and from this a mean damage value was calculated.

The survey showed that a typical large window will belong to a population having a mean square area of 11,198 sq. in. with a standard deviation of 3,186 sq. in. The aspect ratio of this typical window will be 1.436, so that it will measure 88.3 in. by 125.8 in. and have a mean thickness of 0.310 in. It will vibrate at a natural frequency of 5.98 Hz and have a damping ratio of 6.14% of critical. In calculating the probability of damage to each of these 308 windows a sonic boom N-wave with a peak overpressure of 2 psf and durations of 200 ms and 400 ms was used. Furthermore, it was assumed that the window was simply supported and that it will vibrate in the fundamental deflection made. The maximum stress was then calculated for each of the 308 windows, account being taken of the particular geometry and dynamic characteristics in each case.

The results show that for a sonic boom with a peak overpressure of 2 psf and a duration of 200 ms one large window in 9987 will break. For a boom of 400 ms duration, one large window in 13,390 will fail.

In an earlier paper (see capsule summary SR-93) Pavagadhi and Yajnik concluded that a circular elastic plate will show a larger response for a larger boom duration. However, in the present paper it was concluded that a large window is more likely to break in response to a boom of 200 ms duration than to one of 400 ms duration. Since the natural frequency of this typical large window was 5.98 Hz, the results of the present paper indicate that the largest window response will occur when the sonic boom period is approximately equal to the natural period of the window, rather than for the longest boom period.

SR-95

ESTABLISHING AN UPPER BOUND FOR WINDOW RESPONSE TO THE SONIC BOOM

T. V. Seshadri

Journal of Sound and Vibration, Vol. 21, No. 2, 1972, pp 149-158

This paper presents a simple method of estimating the greatest upper bound of stress obtainable in windows due to sonic boom excitation. The effects of damping and nonlinearity are not included. Thus by determining the most severe case for the linear, undamped case, the upper bound is determined, since all actual stress levels must fall below that value.

Only the fundamental mode of vibration is considered, and the window-room system is represented by a lumped element model, similar to the representation used by Koopman and Pollard (see capsule summary SR-77). The results are obtained by solving the various systems of differential equations obtained for the various room-window models considered.

The results obtained are summarized in the two tables below, which were taken from this paper. In the first table the maximum stresses in panels (windows) forming part of one wall of a room opposite to an open hallway are given. The neck length and neck area refer to the characteristics of the hallway and τ is the period of the N-wave. The second table shows the maximum stresses in each of two panels in opposite walls of a closed room. From these tables it can be seen that the structural configuration most likely to suffer a window failure due to sonic boom excitation is one representable by a single large room, a single large window, and an open door. For example, the theoretical upper bound stress of 1400 psf would be encountered in a single window, 10 ft x 8 ft x 1/4 in. in a room of 9000 ft with an opening of 14 ft^2 in response to a sonic boom of 1 lb/ft^2 peak pressure. If the open door were replaced by another window the resultant stresses in both windows would be substantially reduced.

Natural frequency (Hz)	Panel size (ft ft in)	Neck length (ft)	Neck area (ft²)	Volume (ft³)	Maximum stress (lb/in²) Undamped	Damped*	τ
3.07	15 15 [illegible]	10	10	10 000	892	642	0.28
3.74	15 10 [illegible]	10	10	[illegible]	1150	942	0.24
3.52	14 14 [illegible]	10	10	[illegible]	855	408	0.26
4.08	13 13	10	10	6000	789	759	0.22
3.60	12 12 [illegible]	10	10	8000	1170	960	0.24
4.38	12 12 [illegible]	10	10	4000	775	570	0.20
4.87	12 8 [illegible]	10	10	4000	1210	912	0.18
4.31	10 10 [illegible]	10	10	6000	1250	1000	0.20
3.90	10 10 [illegible]	10	10	9000	1540	1200	0.24
5.52	10 8 [illegible]	10	10	4000	1200	980	0.16
4.4	10 8 [illegible]	20	14	9000	1720	1400	0.20
5.4	8 8 [illegible]	10	10	4000	1330	1130	0.16
6.2	8 7 [illegible]	10	10	4000	1300	1195	0.14
7.2	6 6 [illegible]	10	10	2000	1310	1150	0.12
10.2	5 5 [illegible]	10	10	2000	1140	1090	0.10

* [illegible] the door opening and [illegible] at the panel.

Maximum stresses in panels for a 1 lb/ft² N-wave

Window 1 (ft × ft × in)	Window 2 (ft × ft × in)	f_1 (Hz)	f_2 (Hz)	Volume (ft³)	Stress in 1 (lb/in²)	Stress in 2 (lb/in²)
14 × 14 × [illegible]	10 × 10 × [illegible]	3.52	3.90	10 000	335	293
12 × 8 × [illegible]	10 × 6 × [illegible]	3.66	4.40	10 000	790	655
10 × 8 × [illegible]	5 × 5 × [illegible]	5.52	10.4	2000	390	560
10 × 8 × [illegible]	5 × 5 × [illegible]	5.52	10.4	10 000	730	422
8 × 8 × [illegible]	5 × 5 × [illegible]	5.4	10.4	2000	379	610
8 × 8 × [illegible]	5 × 5 × [illegible]	5.4	10.4	10 000	535	367
15 × 15 × [illegible]	5 × 5 × [illegible]	3.07	10.4	10 000	[illegible]90	434
10 × 8 × [illegible]	8 × 8 × [illegible]	5.52	5.4	10 000	602	570
15 × 10 × [illegible]	5 × 5 × [illegible]	3.74	10.4	10 000	565	517
12 × 10 × [illegible]	5 × 5 × [illegible]	2.92	10.4	10 000	767	552
10 × 10 × [illegible]	5 × 5 × [illegible]	3.90	10.4	9000	529	498

Maximum stresses in panels for a 1 lb/ft² N-wave

An earlier study by Knapp and Cheng (see capsule summary SR-62) showed that for overpressures of 1 psf the window stresses predicted by a linear theory and a nonlinear theory were nearly identical. Thus the results of the present study should be fairly close to the actual stress levels, even though nonlinear effects are neglected.

SR-96
SONIC BOOMS IN THE SEA: A RECENT OBSERVATION
R. J. Urick and T. J. Tulko
The Journal of the Acoustical Society of America, Vol. 52, No. 5 (Part 2), 1972, pp. 1566-1568

This is a brief note which presents the results of a flight test measurement of the penetration of a sonic boom beneath the surface of the ocean. In this experiment a Navy F-4 aircraft flew at Mach 1.1 in level flight at an altitude of 1000 feet. Several buoys with hydrophones at a depth of 100 feet were used to relay underwater signals to a Navy P-3C flying overhead at an altitude of 5000 feet. A total of five supersonic runs were made over water 9000 feet deep. The sea was nearly calm, with a surface wind speed of 2 to 5 knots.

The pressure traces showed that the underwater boom occurred ahead of the jet engine noise of the aircraft. It was an irregular blob without the doublet character of the shock wave in air. It had a gradual beginning and gradual ending. This was thought to be suggestive of scattering at the sea surface. Its pressure amplitude was only somewhat greater than that of the jet noise of the aircraft, amounting to only a few dynes per centimeter at the 100-foot hydrophone depth; by contrast, the peak pressure of the sonic boom striking the sea surface was determined to be about 20 psf or 9600 dynes/cm^2. It is concluded that the underwater sonic boom from a low altitude aircraft in level flight has by no means as dramatic an environmental impact as does its counterpart in air and becomes comparable in pressure with the ambient noise background at moderate sea depths.

The results of this study are in agreement with previous experimental studies on the underwater penetration of sonic booms (see capsule summary SR-44, SR-66, and SR-91).

SR-97
THE ACOUSTIC RESPONSE OF ROOMS WITH OPEN WINDOWS TO AIRBORNE SOUNDS
P. G. Vaidya
Journal of Sound and Vibration, Vol. 25, No. 4, 1972, pp. 505-532

The purpose of the work described in this paper and a companion paper (see capsule summary SR-98) was to develop a theory for predicting the sound field in a room which would be generated by a sonic boom incident on an open window. Some basic theoretical results are presented in the present paper. The first case considered was that of a normally incident harmonic wave. The room was treated as a terminated duct and expressions for the pressure field were obtained using a Green function method.

In order to obtain expressions in the time domain for transient signals, a modified form of Laplace transform technique was used. The companion paper discusses the application of these results to the specific problem of sonic booms.

This theory was also described in earlier papers by Vaidya (see capsule summaries SR-72 and SR-73).

SR-98
THE TRANSMISSION OF SONIC BOOM SIGNALS INTO ROOMS THROUGH OPEN WINDOWS
P. G. Vaidya
Journal of Sound and Vibration, Vol. 25, No. 4, 1972, pp. 533-559

This is the second of two companion papers. In the first paper (see capsule summary SR-97), expressions are derived for the acoustic field generated inside a room with an open window by incoming transient or periodic signals. The technique is applied in this paper to the specific example of an N-wave type signal. Approximate forms are developed which enable the theory to be used to make reasonably accurate numerical calculations. A comparison of results obtained using the approximate method with experimental results obtained using simulated sonic booms showed fairly close agreement.

The theory described in this paper and the companion paper is also discussed in earlier papers by Vaidya (see capsule summaries SR-72 and SR-73).

SR-99
A SIGNIFICANT SINGLE QUANTITY THAT TYPIFIES A SONIC BANG
C. H. E. Warren
The Journal of the Acoustical Society of America, Vol. 51, No. 1 (Part 2), 1972, pp. 418-420

This paper proposes a single quantity that typifies a sonic boom. This quantity is called the "characteristic overpressure," defined as 4I/T, where I is the maximum impulse (maximum value of the running integral of the overpressure with respect to time) and T is the signature interval (time interval between the onset of the first shock and the onset of the last shock in the signature). The factor 4 is included so that, in the case of a simple N-wave, the characteristic overpressure is equal to the peak overpressure.

The significance of the characteristic overpressure in regard to the effect of sonic booms on structures is then demonstrated by considering the response of an undamped single-degree-of-freedom system to a sonic boom. This problem was studied extensively by Crocker and Hudson (see capsule summary SR-57). They presented their results in the form of a dynamic magnification factor, which they defined as the ratio of the maximum displacement of the system during the forced motion to the displacement that would occur under a static load equal to the peak overpressure of the waveform. In the present paper the dynamic magnification factor is redefined as the ratio of the maximum displacement of the system to the displacement that would occur under a static load equal to the characteristic overpressure of the waveform.

The results of Crocker and Hudson presented in terms of a dynamic magnification factor normalized on characteristic overpressure are shown to collapse much more closely to a single curve for various sonic boom waveforms than when peak overpressure is used as the normalizing quantity.

It is pointed out by the author that the characteristic overpressure is not subject to much indeterminateness, as some quantities are in practice. The maximum impulse, being the maximum value of a quantity, is not subject to very much interpretation of its value, and the signature interval, being a function of the onsets of shocks, is also fairly easy to determine. Furthermore, both quantities, and thus the characteristic overpressure itself, are readily calculable by the usual sonic boom theory.

Koopman and Orris (see capsule summary SR-84) showed that by using a redefined effective overpressure, in which the impulse is the average of the positive and negative impulses of the N-wave, to normalize the DMF, improved grouping for various types of N-waves is obtained.

SR-100
SONIC BOOMS IN THE SEA
R. J. Urick
Naval Ordnance Laboratory Report No. NOLTR 71-30, February 28, 1971

This paper discusses measurements made below the surface of the sea of sonic booms generated by F-4 and F-8 aircraft flying at Mach 1.1 and 1.2. The measurements were made by means of a string of hydrophones 195 feet long dangling from a surface ship. The horizontal distance between the surface ship and the microphones varied between 100 feet and 300 feet.

The underwater booms were found to decay about as the -3/2 power of the depth below the surface, to have the same spectral content as the sonic boom in air, and to travel down the hydrophone string with the velocity of sound in water. As pointed out by the author, these findings contradict the theories of Sawyers and Cook, which predict an exponential decay with depth, a vertical wavefront, and an attenuation of high frequency components. It is suggested that rough surface scattering may be the causative process for the boom in the sea.

The author points out that the experimental work described in this report is minimal, since only four booms were measured. Furthermore, the noise levels during the recording periods caused by the nearby ship were high. As a result, it is concluded that additional observations, under quiet conditions with more intense booms, is needed.

A later experiment by Urick and Tulko (see capsule summary SR-96) made under calm sea conditions confirmed the results of the present experiment.

7.0 ANIMAL RESPONSE

AR-1
EFFECT OF SONIC BOOMS ON THE HATCHABILITY OF CHICKEN EGGS
Jack M. Heinemann and Eric F. LeBrocq, Jr.
Regional Environmental Health Laboratory, Kelly A.F.B., Texas, Report SST 65-12, February 1965

This report presents the results of an experimental investigation into the effect of sonic booms on the hatchability of chicken eggs. In this experiment five sets of strain-cross White Leghorn hatching eggs, totaling 3415, were exposed to booms for varying periods of time during different portions of the 21-day incubation period. The exposure periods included both the first and third weeks of incubation. These are the weeks of highest embryo mortality under normal hatching conditions. Three sets of the eggs were used as controls and were not exposed. Standard handling procedures used in commercial hatcheries were used for all sets.

Approximately 30 sonic booms were generated daily by F-104 aircraft except for a few days near the end of the test. For the first 12 days, the overpressures outside the building housing the incubators were kept near 5 psf. The overpressures were then raised to 17-19 psf. The median overpressures inside the incubators were 0.75-1.25 psf when the outside pressures were 4-5 psf. The set of eggs exposed for the full test period received over 600 booms. The hatch of this set was 84.3%, compared to a hatch of 84.2% for the control set. The mean hatch of all exposed sets was 83.2%. The unexposed controls had a mean hatch of 81.3%. No gross pathology was found in birds necropsied at twelve weeks of age, and no developmental deviations were found in sample birds examined during the test. It was concluded that sonic booms up to the maximum overpressures involved in the study do not lower or offset hatchability.

This was an important investigation, especially in light of the amount of damage claims that have been submitted by chicken farmers since 1961 claiming sonic boom damage (see capsule summary AR-12). This is the most extensive investigation of its type that has been conducted. Without the results of this test it would have been much harder to refute the invalid damage claims that have been submitted.

AR-2
RESPONSE OF FARM ANIMALS TO SONIC BOOMS
R. B. Casady and R. P. Lehman
Sonic Boom Experiments at Edwards Air Force Base, Interim Report, July 28, 1967, Annex H

This report discusses the results of the experiments conducted, as part of the Edwards Air Force Base sonic boom experiments, concerning the response of farm animals to sonic booms. Ten animal installations were selected for observing animal behavior under sonic boom conditions. These were as follows: 1 race horse breeding farm, 2 beef feeder lots, 2 turkey ranches, 2 chicken ranches, 1 sheep ranch, 1 commercial dairy, and 1 pheasant farm. The number of animals observed were approximately 10,000 beef cattle; 125,000 turkeys; 35,000 chicken broilers; 100 horses; 150 sheep; 320 dairy cattle; and 50,000 pheasants. One beef feeder lot and the horse farm were about 13 miles from the center of the flight corridor, the large turkey ranch was at the end of the corridor within the turning radius of the planes, and the others were adjacent to the corridor 3-5 miles from its center.

The following persons were employed to make the necessary observations as the booms occurred: 14 part-time observers (senior high students), 2 alternates, one camera technician, and one supervisor (high school science teacher). The booms were scheduled Monday through Friday of each week at varying intervals during the morning hours.

The observers were stationed to watch specified groups of animals. They noted behavior patterns of the animals just prior to, at, and immediately following each boom, or disturbance caused by low-flying aircraft used in noise tests.

The following conclusions were reached as a result of this investigation:

1. Except for the avian species, the observed behavior reactions of animals to the sonic booms were minimal. Also, the reactions to noise from low-flying subsonic aircraft were more pronounced than those due to the booms. Furthermore, the reactions were of similar nature and magnitude to those resulting from flying paper; the presence of strange persons, or other moving objects. For these reasons, it was felt that a strong relationship between observed behavior reactions and possible herd or flock production depression is very unlikely.

2. Although no significant changes were noted in production, it was felt that these tests were not adequate to produce any conclusive evidence on this aspect of sonic boom effects. The number of farms available was insufficient for evaluating production effects and their location was not suitable for proper evaluation.

3. It was felt that some of the farm animals may have become considerably adapted to sonic booms prior to those tests, since the area around Edwards Air Force Base had been exposed to about 4-8 sonic booms per day for the previous several years.

The Edwards Air Force Base sonic boom experiments were centered mainly upon obtaining information concerning human response and structural response to sonic booms. The animal response results were in the nature of a by-product and, as a result, the conclusions reached were very preliminary and qualitative in nature.

AR-3
THE EFFECTS OF SIMULATED SONIC BOOMS ON REPRODUCTION AND BEHAVIOR OF FARM-RAISED MINK
H. F. Travis, G. V. Richardson, J. R. Menear, and James Bond
U.S. Department of Agriculture/Agricultural Research Service, ARS 44-200, June 1968

The results of an investigation conducted by the Agricultural Research Service of the U.S. Department of Agriculture concerning the effects of

simulated sonic booms on mink reproduction are discussed in this report. The experiment was carried out on two commercial mink farms in Virginia. The sonic booms were simulated by using the LTV sonic boom simulator described in capsule summary SM-4. The simulated booms had overpressures in the general range from 0.5 to 2.0 psf. Exposure of the test group of female mink to simulated booms began on April 8 (after breeding) and ended on June 1 (after the youngest kit was 11 days old). There were also several control groups of female mink which were not exposed to the booms. The total number of females used in the experiment was 300, and over 1250 kits (baby mink) were involved.

The following conclusions were reached as a result of this experiment:

1. Kit production per female on experiment for the mink receiving the sonic boom treatment was statistically higher than that of the control (724 live kits at 10 days from 180 females for an average per female kept of 4, compared to 427 live kits from 120 females for an average of 3.6. This was primarily because of a higher percentage of females whelping (giving birth).

2. The percentage of females whelping was 91 percent for the boomed mink compared to 78 percent for mink that were not boomed.

3. On a basis of kits per female whelping, the boomed mink had slightly smaller litters (not statistically significant) at 10 days (4.4 kits per female whelping compared to 4.5 kits per female whelping in the groups not boomed).

4. The highest percentage of kit mortality was for mink boomed the entire period. This contributed to slightly higher mortalities in the boomed group and the group whelped at the farm where mink were boomed. However, the overall production (kits per female on experiment) was higher for boomed mink and for mink whelping at the farm where the mink were boomed.

5. There was no effect that could be attributed to differences in sonic boom intensity.

6. There were no visible indications that the repeated booming caused increased excitability or nervous reactions in the mink that were boomed.

7. There was no evidence observed from autopsies of the dead kits that indicated mortality because of the effects of the sonic boom.

The amount of money awarded in damage claims to mink farmers since 1961 (see capsule summary AR-12) accounts for nearly 75% of the total amount of money awarded in all types of animal damage claims. The present investigation was the first study conducted to determine just what effects sonic booms do have on mink. Prior to this investigation there was no experimental basis for refuting the damage claims of the mink farmers. However, as pointed out by Bell in the paper described in capsule summary AR-12, mink farmers questioned the results of the present investigation on the basis that the booms were simulated and not real, and also on the basis that the female mink were exposed to booms prior to whelping, thus giving them time to adjust. For this reason, a later investigation was carried out using both simulated and actual son oms (see capsule summary AR-14) in which the ex re to booms began after whelping. The results were similar to those of the present investigation.

AR-4

SONIC BOOMS RESULTING FROM EXTREMELY LOW-ALTITUDE SUPERSONIC FLIGHT: MEASUREMENTS AND OBSERVATIONS ON HOUSES, LIVESTOCK AND PEOPLE

C. W. Nixon, H.K. Hille, H.C. Sommer, and E. Guild
Aerospace Mecical Research Laboratoreis, Wright-Patterson A.F. Base, Ohio, Report No. AMRL-TR-68-52, October 1968.

In the flight-test experiment described in this report, sonic booms generated by F-4C aircraft flying low-level terrain-following profiles during joint Task Force II operations near Tonopah, Nevada, were recorded under and near the flight tracks, and responses of structures, animals, and people were observed. The overpressure levels varied between 80 and 144 psf directly under the flight track. Only the animal response findings will be discussed here. For a discussion of the human response and structural response results, see capsule summaries HRSC-89, and SR-37, respectively.

No concentrations of cattle or horses were found directly under the flight corridors, even though they were established over the open range. Several small groups of cattle near the tracks and a horse in a corral were observed and their responses to, during, and following sonic boom were recorded on movie film. The responses were either unrecognizable or consisted of an apparent alerting response accompanied by trotting off a short distance. Also, ranchers reported no observable response to the sonic booms of the livestock at various other locations on the range.

Some of the livestock and cattle observed during this program annually winter grazed on the Sandia range and consequently were previously exposed to low-flying aircraft, sonic booms and explosive blasts. Thus, it is pointed out by the authors that the lack of adverse response during this program cannot be generalized to other cattle and horses in other parts of the country.

The results of this test concerning animal response to sonic booms are very inconclusive, but they do indicate that exposure of livestock to extremely intense sonic booms will not result in injury.

AR-5

DAMAGE EXPERIENCE

William F. McCormack
Proceedings of the Conference, Noise as a Public Health Hazard, Washington, D.C.-June 13-14, 1968, in ASHA Reports 4, The American Speech and Hearing Association, February, 1969, pp. 270-277

A summary of damage claims presented to the U.S. Air Force as a result of sonic booms is presented in this paper. Only the portion of the paper dealing with animal claims is summarized here. For a discussion of the remainder of the paper, see capsule summary SR-52.

Between 1962 and April 1968 only 192 claims involving damage to animals were processed by the Air Force. This compares to a total of 35,094 claims in all damage categories. A breakdown of these claims is shown in the table below, which was taken from this paper. Injuries resulting from startle and panic were involved in a high percentage of these claims. Claimants often alleged that the productivity of female animals was affected by the startling effect of a sonic boom, such as loss of poultry production. The hatchability of eggs was alleged to have been affected by sonic booms in other cases. The claims wer- .en somewhat speculative as to the cause of d· :, such as when an animal was discovered to injured itself sometime during the time span w.. n a sonic boom occurred.

Category	No. of Claims	Dollars Claimed	No. Approval	Dollars Paid
Hogs	1	$ 125.00	1	$ 87.00
Rabbits	4	900.00	1	350.00
Pheasants	3	19,200.00	1	17.00
Turkeys	11	51,706.00	4	18,608.00
Mink	18	205,420.00	12	25,926.00
Eggs	18	7,163.00	1	3.00
Dogs	20	3,821.00	3	146.00
Cattle	23	10,162.00	13	3,569.00
Horses	35	43,943.00	15	5,604.00
Chickens	45	85,018.00	21	6,256.00
Other	14	57,330.00	4	381.00
Total	192	$484,796.00	76	$60,946.00

All animal claims processed since 1962 by the Air Force

An updated table of animal claims damages was given by Bell in the paper described in capsule summary AR-12.

AR-6

THE EFFECT OF SONIC BOOM EXPOSURE TO THE GUINEA PIG COCHLEA
Deborah A. Majeau-Chargois, Charles I. Berlin, and Gerald D. Whitehouse
NASA CR-102461, October 29, 1969

In the experiment described in this report, guinea pigs were subjected to controlled sonic booms in order to objectively evaluate damage to the auditory mechanism. Thirty guinea pigs with normal hearing were used. Six were controls and eight each were exposed to 1000 sonic booms at approximately 130 dB of 2, 4.76 and 125 msec N-wave pulse duration, respectively. The simulated booms were produced in a one-foot diameter plane-wave tube, 20 feet long with a 30" speaker mounted at the end of the tube. To produce the pulse a Wavetek Mod-l III oscillator was set to deliver N-waves and fed into a GR tone burst generator Type 1396A. Boom exposure was at the rate of one per second. The fundamental frequency of the N-wave was either 210 Hz, 500 Hz, or 8 Hz.

After exposure, the guinea pigs were sacrificed (at various intervals) and their cochleae examined. It was found that hair cell damage occurred in the apical turn of the cochleae of the exposed guinea pigs,while the other turns were unaffected. Damage occurred in the same place with all pulse signatures tested. Since the sacrifice of the guinea pigs ranged from 24 hours to 2 weeks after exposure, it was felt that the damage to the hair cells was permanent.

In spite of the hair cell damage, it was found that the hearing of the exposed guinea pigs, as measured by conditioned response tests, did not show any sign of impairment. As a result of this it is hypothesized that sonic booms conducted with human subjects might reveal no impairment of auditory function while, in fact, damage may be present Such a weakening could, in time, affect other areas, thereby aiding the development of a hearing loss.

It is pointed out that a valid question could be raised that presenting sonic booms every second could be more detrimental than exposure of once or twice a day, which would be more realistic in the normal community. It is concluded that additional research would have to be undertaken to clarify the test.

Although the results of this report indicated that possible harm to the human auditory system could result from intense sonic booms; the results are fa. from conclusive.

AR-7

SONIC BOOM EFFECTS ON THE ORGAN OF CORTI
Deborah A. Majeau-Chargois, Charles I. Berlin, and Gerald D. Whitehouse
The Laryngoscope, V. 80, April 1970, pp. 620-630

This paper is the same as the one discussed in capsule summary AR-6. The reader is referred to that capsule summary for details.

AR-8

EFFECTS OF NOISE ON THE PHYSIOLOGY AND BEHAVIOR OF FARM-RAISED ANIMALS
James Bond
Physiological Effects of Noise, Edited by Bruce L. Welch and Annemarie S. Welch, Plenum Press, New York-London, 1970, pp. 295-306

This paper presents a general review of literature on sound effects on farm animals and of specific studies conducted which deal with this topic. The portion of the paper dealing with the effects of sonic booms on farm animals summarizes the findings made in the Edwards Air Force Base sonic boom experiments (see capsule summary AR-2) and in the experiment dealing with the effect of sonic booms on mink reproduction (see capsule summary AR-3). The reader is referred to the above two capsule summaries for a discussion of those results.

AR-9

MASS HATCHING FAILURE OF DRY TORTUGAS SOOTY TERNS
W. B. Robertson, Jr.
Paper Presented to 14th International Ornithological Congress, Holland, 1970

A discussion of the mass hatching failure of the Dry Tortugas colony of Sooty Terns in 1969 is presented in this paper. This colony of about 40,000 breeding pairs nests each spring on Bush Key off the coast of Florida. A nearly continuous annual record has been kept of the colony since 1903. During the period from 1959-1968 and again in 1970, an estimated 25,000 to 30,000 young were born. In 1969, however, most of the Sooty Tern eggs did not hatch and only 300 to 400 young were born.

The possible causes of this mass hatching failure that were investigated are as follows: (1) weather; (2) predation; (3) food shortage; (4) dense vegetation in the colony; (5) pesticides; and (6) disturbance by man. It is shown that the weather conditions, predation, food shortage, and vegetation in the colony were no more severe than in previous years. As a result, these factors were eliminated as a likely cause. A chemical analysis made of a number of Sooty Terns and Sooty Tern eggs showed that chemical pollutants (such as pesticides) were not likely to have been involved in the mass hatchery failure.

No unauthorized landings are permitted on Bush Key during the nesting season, and, since there is almost constant surveillance, the rule is seldom broken. No record exists of any unauthorized landings in 1969. Thus the only man-caused disturbances that occurred during the nesting season of 1969 were due to low-flying airplanes and helicopters and sonic booms, most of which originated from planes at high altitudes. It is stated the overflights of subsonic jets at altitudes below 500 feet invariably trigger mass panic flights of Sooty Terns. However, the birds usually return to their nests within 10 minutes, and no harm is done to the eggs. During the spring of 1969 the number of aircraft overflights and high-altitude sonic booms did not appear to be significantly greater than in previous years. However, National Park Service personnel reported three unusually severe sonic booms in early May, 1969. The first and most intense occurred on May 4. It broke several windows on Garden Key (adjacent to Bush Key) and dislodged mortar from the crumbling masonry of Fort Jefferson (on Garden Key also). The other severe sonic booms occurred on the 8th or 9th of May and May 11. The airplanes causing the sonic booms were not seen by any of the observers. However, they thought from the severity of the shocks that the airplanes had overflown Tortugas at extremely low altitude.

Observations of the date that the eggs were laid together with examinations of the age of the dead embryos in the eggs that failed to hatch placed the date of the hatching failure between the 1st and 9th of May. The only known events that were properly timed and also possibly sufficient to cause mass death of embryos in Sooty Tern eggs were the sonic booms on May 4 or May 8 or 9. The boom of May 4, in particular, was thought by observers to have been very much more severe than any previously experienced at dry Tortugas. Since it was sunny and clear on May 4, and Sooty Terns commonly do not incubate during the middle of warm days but merely shade the eggs, most of the eggs were probably completely exposed to the sonic boom.

It is concluded that physical damage to the eggs caused by a severe sonic boom most adequately explains the mass hatching failure. However, it is pointed out that the case is wholly circumstantial.

This is a very excellent and interesting paper. Although the final conclusion attributing the mass hatching failure to a severe sonic boom is based upon circumstantial evidence, this evidence is very convincing.

AR-10

EFFECTS OF NOISE ON WILDLIFE AND OTHER ANIMALS
Memphis State University
U.S. Environmental Protection Agency, Report No. NTID300.5, December 31, 1971

A very comprehensive review of the literature dealing with the effects of noise on wildlife and other animals is presented in this paper. The studies concerning the effects of sonic booms on animals that are mentioned here are those of Casady and Lehman (see capsule summary AR-2), Heinemann and Le Brocq (see capsule summary AR-1), Travis, et al. (see capsule summary AR-3), and Majeau-Chargois, et al. (see capsule summary AR-6). The reader is referred to the capsule summaries of those papers for a discussion of their findings.

AR-11

SONIC BOOM EFFECT ON FISH - OBSERVATIONS
Max E. Wilkins
Unpublished paper, NASA Ames Research Center, Moffett Field, California, 1971

The results of an experimental investigation into the effects of sonic booms on fish are presented in this paper. The investigation was conducted in the Pressurized Ballistic Range at the Ames Research Center. Bullets having a muzzle velocity of 3900 ft/sec ($M = 3.5$) were fired from a 0.22 Swift rifle. The flight path of the bullets was 11-1/2 cm above the water surface of a 15-1/4 by 15-1/4 by 30-1/2 cm-long clear tank located about 20 m from the rifle. The tank contained five guppies, and their reactions were recorded on 8-mm film as the bullets, generating shock waves with overpressures of 550 psf, passed overhead.

It was found that the fish usually reacted to the passage of the shock wave. However, the reaction was not violent. It consisted of a flinching motion occasionally followed by a rapid movement, generally downward. There was a greater reaction shown by fish near the surface than by those near the bottom. The fish that did react did not appear to be alarmed and settled down immediately.

No ripples were observed on the water when the bullet passed over. It was felt that this ruled out any influence the wake of the bullet might have had on the fish.

The exposed fish were kept isolated for observation for two months after the tests, and no adverse effects due to the boom were noted. It was concluded that, although fish react to the overhead passage of a strong shock wave, they do not suffer any harm.

There has been much concern about the effects of sonic booms on fish and other marine life, since trans-oceanic commercial supersonic flight is not forbidden. However, very little research has been conducted on this topic. This investigation provided the first definite experimental indication that even extremely intense sonic booms will not harm fish.

AR-12

ANIMAL RESPONSE TO SONIC BOOMS

Wilson B. Bell

Sonic Boom Symposium, The Journal of the Acoustical Society of America, Vol. 51, No. 2 (Part 3), February 1972, pp. 758-765

A review of reports and studies of animal response to sonic booms is presented in this paper. Included in the review are the studies made by Heinemann, et al (see capsule summary AR-1). Casady and Lehman (see capsule summary AR-2), Nixon, et al (see capsule summary AR-4), Travis, et al (see capsule summary AR-14), Robertson (see capsule summary AR-9), and Majeau-Chargois (see capsule summary AR-6). The reader is referred to the appropriate capsule summary for details of these studies. In addition to a summary of these studies, several others, including some previously unpublished information, are summarized.

A table, shown below, is given which summarizes the claims received and amounts paid by the U.S. Air Force fo. damage to animals during the period from 1961-1970. McCormack (see capsule summary AR-5) published a similar but earlier table.

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U. S. Air Force Disposition of sonic boom animal claims, 1961-1970

A review is made of the limited data available on the reactions of wild animals and birds to sonic booms. The following are some of the findings of the review:

1. Wild deer at Elgin Air Force showed no apparent response to sonic booms of very high intensity.

2. Zoo animals show only alertness and momentary concern about sonic booms.

3. It was found in one study that sonic booms generated at cruising altitude did not seem to affect the behavior of reindeer.

This is an excellent summary of the state of knowledge concerning animal response to sonic booms as of 1971.

AR-13

EXPERIMENTS ON THE EFFECT OF SONIC-BOOM EXPOSURE ON HUMANS

Ragnar Rylander, Stefan Sorensen, Kenneth Berglund, and Carina Brodin

Sonic Boom Symposium, The Journal of the Acoustical Society of America, Vol. 51, No. 2 (Part 3), February 1972, pp. 790-798

In the experiments described in this paper the effects of sonic boom exposure on the reactions humans and reindeer were studied in a field exposure experiment. Only the results concerning the response of the reindeer will be discussed here. For a discussion of the human response results, the reader is referred to capsule summary HRSC-73.

The purpose of the reindeer study was to determine the occurrence of exposure effects which could be of importance for reindeer breeding. Forty-two sonic booms with levels varying from about 0.2 to 10.5 psf were generated by Swedish military aircraft flying over a research camp in northern Sweden. A group of 24 male and female reindeer, picked at random from a larger herd, was kept in a corral in the research camp. Their behavior was recorded on 16-mm film from a 3-m-high observation tower in the middle of the corral. Immediate changes in the activities of the animals were used as exposure-effect criteria.

The following results were obtained from this experiment:

1. Sonic booms below about 0.5 psf were found to cause a slight startle effect. This was manifested as a temporary general muscle contraction. Activities in which the animals were engaged were interrupted only infrequently and then only for a short time.

2. An increase in the impact and occurrence of the reaction was noted as boom levels increased. The effects were, however, never strong enough to bring resting animals upon their feet. Animals in sleeping position raised their heads, pointed their ears, put up their noses, and sniffed in different directions for a few seconds, whereafter they resumed their sleeping postures. Animals which were ruminating reacted in a similar manner, and the ruminating was never interrupted. A more marked startle reaction was shown by grazing animals. They rapidly raised their heads, pointed their ears forward and looked around for a few seconds before resuming their grazing.

3. No differences were found between animals of various ages or sexes.

4. No signs were noted during the experiment of adaptation to the startle reaction.

5. No panic movements were observed. Animals did not change their positions during or after the exposure.

6. Birds and field mice were abundant in the area, and the apparent effects of the booms on these animals was negligible.

Several earlier experiments had investigated the effects of sonic booms on cattle, horses, and other domesticated animals (see capsule summaries AR-2 and AR-4, for example). However the results found in those experiments could not be extrapolated to reindeer, since reindeer are much more nervous. Thus the present investigation served a useful purpose.

AR-14

AN INTERDISCIPLINARY STUDY OF THE EFFECTS OF REAL AND SIMULATED SONIC BOOMS ON FARM-RAISED MINK (MUSTELA VISON)

Hugh F. Travis, James Bond, R. L. Wilson, J. R. Leekly, J. R. Menear, C. R. Curran, F. R. Robinson, W. E. Brewer, G. A. Huttenhauer, and J. B. Henson

Federal Aviation Administration, Report No. FAA-EQ-72-2, August 1972

This report discusses an investigation conducted on Mitkof Island, Alaska, in 1970 to determine the effects of real and simulated sonic booms upon late pregnancy, parturition, early kit mortality, and subsequent growth of farm-raised mink. The reproduction study was conducted using 350 yearling and 148 2-year-old females and their 1,845 progeny. The growth study was conducted with 90 male and 90 female kits (baby mink). The exposed animals received either three sonic booms averaging 5.05 psf overpressure (range 6.6 to 3.6 psf) or three simulated sonic booms generated by the LTV exponential-horn-type sonic boom simulator (see capsule summary SM-4). The simulated booms had an overpressure intensity which ranged from 5.84 psf for the mink nearest the simulator to 1.6 psf for the most distant mink. In each case the exposure was made on the day approximately 40 percent of the females in each group had whelped (given birth). The booms were given over a 60-minute period, the second following the first by 45 minutes, and the third following the second day by 15 minutes. Control animals were not boomed.

The following are the most significant results obtained in this experiment:

1. No differences were found among the experimental treatments for length of gestation, number of kits born per female whelping, number of kits alive per female at 5 and 10 days of age, weight of kits at 49 days of age, kit pelt value, and selling price.

2. A behavioral study showed no evidence that the female mink under observation were sufficiently disturbed by sonic booms to engage in kit packing, kit killing or to disrupt normal lactation.

3. Results of necropsy examinations showed no mink deaths attributable to real or simulated sonic booms. Also, no evidence was found that bacterial disease was induced in the herd following exposure to sonic booms.

4. There were no detectable differences in the overall health of the females at the three sites (control, boom, and simulated boom).

The overall conclusion drawn from these results was that exposure of farm-raised mink to intense sonic booms during whelping season had no adverse effect on their reproduction or behavior.

An earlier investigation was conducted which was very similar to the present investigation except that only simulated sonic booms were used and the females were exposed to the booms both before and after whelping. Mink farmers questioned the results of that investigation, which were similar to those of the present investigation, on the basis that the booms were simulated and that the exposure began prior to whelping, thus giving the females time to adjust. The present experiment was designed to overcome the objections raised to the earlier results.

ARC-15

SONIC BOOM EXPOSURE EFFECTS II.5: EFFECTS ON ANIMALS

Ph. Cottereau

The Journal of Sound and Vibration, Vol. 20, No. 4, 1972, pp. 531-534

This paper presents a review of studies that have been conducted concerning the effects of sonic booms on animals. The studies that are briefly summarized include those by Heinemann (see capsule summary AR-1), Casady and Lehman (see capsule summary AR-2), and Travis, et al. (see capsule summaries AR-3 and AR-14). Also mentioned are several French studies.

In one of the French tests comparisons were made between the behavior of broilers in two poultry farms, one of them exposed to simulated sonic booms of about 2 psf intensity. Tests were made on the growth of the broilers during breeding and laying. The preliminary results showed that broilers which had been exposed since their birth to sonic booms at a rate of three every morning every day showed a startle reaction and stopped all activity for 20 to 30 seconds following each boom.

Another French study was concerned with the effects of sonic booms on chick embryos during hatching. In this experiment chick embryos in hatching were exposed to three sonic booms every morning and three every evening. It was found that the chicks from these eggs were normal.

Wilson (see capsule summary AR-12) gave a much more extensive and complete review in an earlier paper of the studies that have been conducted concerning animal response to sonic booms.

AR-16

EFFECT OF SONIC BOOM ON FISH

Robert R. Rucker

FAA Report No. FAA-RD-73-29, February 1973

The results of a series of experiments conducted to determine the effect of sonic booms on fish and fish eggs during critical stages of development are discussed in this report. The experiments consisted of both field and laboratory tests conducted at several National Fish Hatcheries.

Fish eggs reach a critical period at a certain stage during their development where they become sensitive to vibration or disturbance. The program described in this paper was designed to determine if the disturbances caused by sonic booms could have a detrimental effect during this period. The procedures consisted of rearing eggs from both trout and salmon in the normal manner, except that they were exposed to sonic booms produced by military airplanes during their most critical phase of development. The overpressures involved in the various tests ranged from less than 1 psf to over 4 psf.

In each experiment a control group of eggs spawned at the same time as the experimental group was reared in a separate location which was not exposed to sonic booms. The number of egg and fish fry mortalities for each of the two groups was then compared. The results of the comparisons indicated that the sonic boom exposure caused no increase in mortality.

In an additional laboratory study that was conducted, salmon eggs were exposed in a simulator to sonic booms from 0.55 psf to 4 psf overpressure at regular intervals during their development. The eggs were raised to the feeding stage and compared with a control group of eggs raised in the normal undisturbed manner. No noticeable increases in mortality or influence on normal development were found.

It is concluded that exposure to sonic booms of the magnitude characteristic of commercial airplane operations will not have a detrimental effect either on fish spawning in nature or those spawning in hatcheries.

This was an excellent investigation and it was the first to investigate the effect of sonic booms on fish eggs. The only other investigation that has been conducted concerning the effects of sonic booms on fish was made by Wilkens (see capsule summary AR-11). That study used a ballistic range test to show that guppies react to very intense sonic booms but are not harmed by them.

AR-17
REPORT ON THE SONIC BOOM PHENOMENON, THE RANGES OF SONIC BOOM VALUES LIKELY TO BE PRODUCED BY PLANNED SST'S, AND THE EFFECTS OF SONIC BOOMS ON HUMANS, PROPERTY, ANIMALS, AND TERRAIN
Attachment A of ICAO Document 8894, SBP/II, Report of the Second Meeting of the Sonic Boom Panel, Montreal, October 12 to 21, 1970

This report is composed of six chapters, each dealing with a certain aspect of sonic boom phenomena. The present capsule summary summarizes only Chapter [illegible], which is entitled "Sonic Boom Effects on the Animal Kingdom."

The results of the various studies that have been conducted concerning animal response to sonic booms and the animal damage claims that have been submitted as a result of sonic booms are reviewed in Chapter [illegible]. The following conclusions were reached as a result of this review:

1. There are varying reactions of startle, ranging from mild (e.g. head-raising, bellowing in a few percent of the large farm animals) to severe (crowding or pandemonium in 8% of chickens in one survey).

2. Claims abjudications have awarded significant amounts for animal startle effects which have not been substantiated in controlled experiments.

3. There are no measurable effects of sonic boom on egg production (except for one case of a marked drop for pheasants where other adverse effects were present), milk production, and food consumption.

4. The effects of habituation for both sensitive animals as well as domesticated animals have not been determined.

5. The effects of sonic boom on terrestrial wildlife are largely unreported.

6. The effects of sonic boom on aquatic life are unreported. However, the first results concerning the attenuation of sonic boom in water suggest that these effects should be small.

This is a good summary of the state of knowledge as of 1970 concerning animal response to sonic booms.

8.0 THRESHOLD MACH NUMBER

TM-1
METHODS FOR ESTIMATING DISTRIBUTIONS AND INTENSITIES OF SONIC BANGS
D. G. Randall
Aeronautical Research Council Technical Report, R. M. No. 3113, 1959

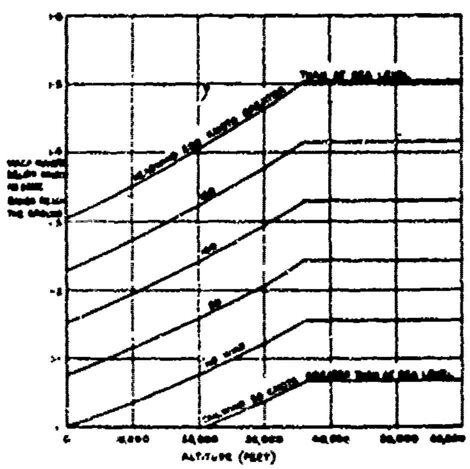
This paper is basically concerned with the propagation of sonic booms in a stratified atmosphere. For a discussion of that portion of the paper the reader is referred to capsule summary P-21. The present capsule summary discusses only the portion of the paper which deals with the intensification of sonic booms on the ground due to flight at the threshold Mach number. This intensification is due to the convergence of the sound rays as their slopes become horizontal.

The following simple equation is given for predicting the aircraft speed at which no booms will reach the ground:

$$V - \Delta\omega < a_g$$

where V = airplane speed
$\Delta\omega$ = amount that headwind speed at aircraft altitude exceeds that on ground
and a_g = speed of sound at ground level.

The figure below, which was taken from this paper, shows the results predicted by this equation for various altitudes and wind speeds.



Threshold Mach number vs altitude

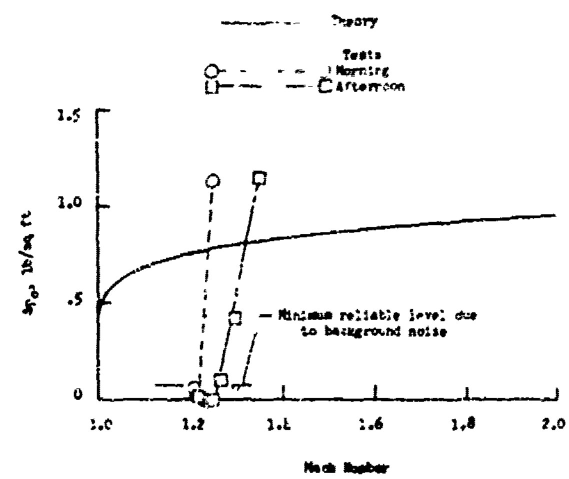
An estimation is made of the amount of intensification that results from the convergence of the rays at ground level caused by flight at the threshold Mach number by computing the overpressure that results when all of the disturbances produced by the aircraft over a given portion of its flight path arrive at the same point simultaneously. However, the resulting equation overestimated the intensification because second order effects were ignored. The reader is referred to capsule summary TM-13 for the results of an experimental investigation of the intensification at the caustic resulting from flight at the Threshold Mach number.

This was the first theoretical treatment of threshold Mach number flight. The equation given here for the aircraft speed at which no booms will reach the ground is essentially the same as the one used later by Kane and Palmer (see capsule summary TM-3) for computing the cutoff Mach number.

TM-2
GROUND MEASUREMENTS OF AIRPLANE SHOCK-WAVE NOISE AT MACH NUMBERS TO 2.0 AND AT ALTITUDES TO 60,000 FEET
Lindsay J. Lina and Domenic J. Maglieri
NASA TN D-235, March 1960

In the investigation described in this report, measurements of sonic boom and overpressures were made near the ground track for flights of a supersonic fighter and one flight of a supersonic bomber. Most of the results deal with sonic boom generation theory, and for a summary of these results the reader is referred to capsule summary G-9 . The present capsule summary discusses only that portion of the results dealing with flight near the cutoff Mach number.

The figure below, which was taken from the paper, shows a comparison of measured data near the cutoff Mach number, and values predicted using Whitham's asymptotic theory (see capsule summary G-3). The figure shows that the sonic boom intensity decreased as Mach number was decreased to the cut-off Mach number and the maximum value of ΔP_o obtained was only about 40 percent greater than that predicted by Whitham's theory. It is hypothesized that this result may be in some way related to the focusing effect of refraction. It is pointed out, however, that the large intensification at the cut-off Mach number predicted by Randall's theory (see capsule summary TM-1) was not detected.



Shock strength variation near cutoff Mach number

The arrival times were the same for both free air and ground microphones (vertically displaced) indicating, as expected, that the shock wave was perpendicular to the ground at the cut-off Mach number. Furthermore, no reflected wave was seen on the free-air trace, and the intensity measured by the free-air microphone was the same as that measured by the ground microphone.

The cut-off Mach number, predicted from rawinsonde data using the equation proposed by Randall (see capsule summary TM-1), was 1.22, which agreed with the measured cut-off Mach numbers within about ±0.03.

A discussion is then presented of the effect of flight-path angle on the cut-off Mach number. On the basis that flight-path angle changes are equivalent to changes in the Mach angle as far as propagation direction is concerned, the following relation is given for determining the variation of cut-off Mach number with flight-path angle:

$$M_\gamma = \frac{1}{\sin\left(\sin^{-1}\frac{1}{M_L} - \gamma\right)}$$

where M_γ = cut-off Mach number for flight path angle
and M_L = cut-off Mach number for steady level flight

A climb maneuver made at a combination of flight-path angle and Mach number close to the condition at which cut-off was predicted resulted in a measured overpressure of 0.07 psf compared to an overpressure 0.56 psf for level flight at the same Mach number and altitude. This result indicated that cut-off did occur, as predicted.

This was the first flight-test investigation in which measurements were made of the pressure signatures resulting from steady level flight at speeds near the threshold Mach number. A similar investigation was made later by Maglieri and Hilton (see capsule summary TM-5) leading to similar results. However, neither of these investigations was as extensive as the one made by Haglund and Kane (see capsule summary TM-13).

TM-3
METEOROLOGICAL ASPECTS OF THE SONIC BOOM
Edward J. Kane and Thomas Y. Palmer
Federal Aviation Agency SRDS Report No. RD 64-160, September 1964

This report presents an extensive analysis of atmospheric effects on the propagation of sonic booms. This analysis is summarized in capsule summary P-42. The present capsule summary discusses only the portion of the paper dealing with the complete cut-off of the shock wave that occurs for flight at Mach numbers below the "cutoff" Mach number.

The following expression is given for the largest Mach number at which complete cutoff of the shock wave takes place:

$$M_{cut\text{-}off} = \frac{(a+U)_{max} - U_a}{a_A}$$

where a = sound speed at some level between the airplane and the ground
U = tailwind speed component at the same level as selected for a (U is negative if it is a headwind component)
U_a = tailwind component at airplane (U_a is negative if it is a headwind component)
a_A = sound speed at airplane
$(a+U)_{max}$ = largest value of sound speed and wind component speed which occurs between the airplane and the ground.

From this formula it can be seen that a headwind increases the cut-off Mach number and a tailwind decreases it.

Focusing under the flight track, which occurs for flight at the threshold Mach number, is then discussed. Focusing takes place when cut-off occurs at the ground. The following formula is given for determining the Mach number at which focusing on the ground may occur.

$$M_{FOCUS} = \frac{(a+U)_g - U_a}{a_A} \text{ if and only if } (a+U)_g = (a+U)_{max}$$

where $(A+U)_g$ = sum of sound speed and tailwind component at the ground.

If the quantity (a+U) is not largest at the ground, cutoff and possible focusing will occur at the level where this quantity has its greatest value. Thus focusing at the ground will occur only when the cut-off Mach number is equal to the threshold Mach number. The above formula, therefore, also gives the threshold Mach number.

In another portion of the paper it is pointed out that as the shock wave becomes perpendicular to the ground the reflection factor must change in some manner from 2.0 to 1.0. Thus the focusing effect that occurs when the shock wave becomes perpendicular to the ground will be of a reduced nature, as a result of the smaller reflection factor.

The equation given in this report for determining the cutoff Mach number has been used in nearly all later investigations dealing with threshold Mach number operations (see capsule summaries TM-4, TM-5, TM-6, TM-7, TM-8, TM-9, and TM-13). The prediction made in this report that the reflection coefficient changes from 2.0 to 1.0 as the shock wave becomes perpendicular to the ground was verified by the results of a later experimental investigation (see capsule summary TM-13). Thus, although the portion of this paper dealing with flight near the cutoff Mach number is brief, two significant contributions to the theory were made.

TM-4
AIRLINE OPERATION OF MODEL 742-228 TRANSONIC TRANSPORT NEAR CUTOFF MACH NUMBER
D.E. Cuadra and R.A. Mangiarotty
Boeing Company Document D6-14024 TN, November 1965

This report presents the results of a study conducted to determine the variation in cutoff Mach number over the Los Angeles-New York route for mean and 95% probabilities of meteorological conditions, assuming flight at 45,000 feet pressure altitude. Also included in the study is a calculation of the probability of exceeding the actual cutoff Mach number if a Mach number schedule based on available airline weather data is used and flight is held to 0.02 Mach less than the cutoff predicted by the 95% meteorological profiles.

The mean (most probable) and the 95% (2σ) wind intensities and temperature profiles were compiled for nine stages between New York and Los Angeles, and the resulting cut-off Mach number was computed for each of these stages for the months of January, April, July, and October. Based on these results, the probability of exceeding the actual cutoff Mach number anywhere along the route when the aircraft

speed along the route is held to a Mach number schedule based on available airline weather data at the beginning of the flight, and the flight is held to 0.02 Mach less than the cutoff predicted by the initial 95% profiles was determined to be about 3%.

The influence of the jet stream on domestic routes is then discussed. The main effect is that it results in lower cutoff Mach numbers on west-to-east than east-to-west flights. The main problem with jet stream winds is that it is difficult to forecast them accurately.

It is pointed out in a later paper by Haglund (see capsule summary TM-9) that the use of statistical atmospheric data in the present paper gives a fairly accurate mean threshold Mach number, but it results in a significant underestimation of the variability of the threshold Mach number. The correct method of determining the climatology of the threshold Mach number, Haglund points out, is to use a large number of atmospheric soundings of temperature and wind to compute a large number of threshold Mach numbers, and then to perform the statistical analysis on the threshold Mach numbers themselves.

TM-5

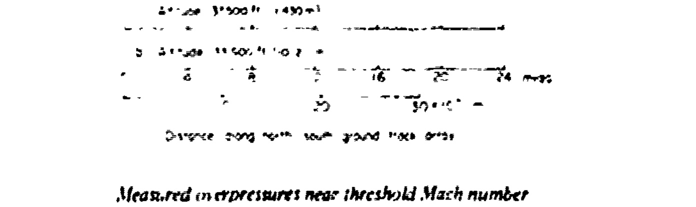
EXPERIMENTS ON THE EFFECTS OF ATMOSPHERIC REFRACTION AND AIRPLANE ACCELERATIONS ON SONIC-BOOM GROUND PRESSURE PATTERNS

Domenic J. Maglieri, David A. Hilton, and Norman J. McLeod

NASA TND -3520, July 1966

The results of a flight-test investigation of the effects of atmospheric refraction and airplane accelerations on sonic boom ground pressure patterns are presented in this paper. The present capsule summary discusses only the portion of the paper dealing with the signatures measured for steady level flight at cutoff Mach number. For a summary of the results presented in the remainder of the paper, see capsule summary P-60.

Five supersonic flights were conducted in an attempt to better define the grazing condition. The results are shown in the figure below, which was taken from this paper. The figure shows that, for the cases in which booms were heard, the measured overpressures fell between the value calculated from Whitham's asymptotic theory (see capsule summary G-3) using a reflection factor of 1 and the value calculated using a reflection factor of 2. This is in agreement with the prediction made by Kane and Palmer (see capsule summary TM-3) that the reflection factor must change from [illegible].0 for a weak oblique shock front to 1.0 for a normal shock front.



Measured overpressures near threshold Mach number

The results shown in the figure also suggest that there might be a tendency for pressure build-ups due to grazing but because of the relatively low reflection factor for this condition the resulting ground overpressure values are of the same order of magnitude as those predicted for steady level flight at higher Mach numbers. Definite shock-type signatures were observed for Mach numbers well above grazing, and for Mach numbers well below grazing, no booms were observed. At Mach numbers just slightly below grazing, the signatures observed were believed to be acoustic in nature.

This was the second flight-test investigation concerning threshold Mach number flight. The first was conducted in 1960 (see capsule summary TM-2). Both of these investigations obtained similar results. The most extensive investigation of threshold Mach number flight was made by Haglund and Kane in a later report (see capsule summary TM-13).

TM-6

PASSENGER TRANSPORT AT LOW SUPERSONIC SPEEDS

E. S. Bradley, W. M. Johnston, and C. H. von Keszycki

AIAA Paper No. 69-776, Presented at AIAA Aircraft Design and Operations Meeting, Los Angeles, California, July 14-16, 1969

This paper presents preliminary study results for a commercial passenger transport cruising at Mach 1.15. Included in this study are the following topics: (1) effects of non-standard atmospheric conditions in temperature and wind on the cruise Mach number and ground speed for which sonic boom cut-off occurs on the ground; (2) characteristics of ground-observed overpressure signatures in the event of an accidental excess of speed beyond the limit ensuring occurrence of a cut-off above the ground level; and (3) a preliminary configuration study of a low-supersonic transport.

The discussion concerning the effects of non-standard atmosphere conditions on the cutoff Mach number is very brief. It shows that the threshold Mach number can vary from 1.02 for a cold day with a tailwind to 1.24 for a standard day with a headwind. The cruise design Mach number for this study was arbitrarily chosen as $M = 1.15$, which is equal to the cut-off Mach number for standard atmospheric conditions.

The investigation of the characteristics of the pressure signatures resulting when the cutoff Mach number is exceeded slightly resulted in the conclusion that they would probably be more acceptable than those resulting from a high-speed SST. This conclusion was based on the hypothesis that a near field signature would exist for an aircraft with a fuselage length of 350 feet cruising at an altitude of 40,000 to 50,000 feet, and the possibility that the signature might be of the acoustic type, having no shock waves.

The aircraft selected for the preliminary design study was a 450 passenger commercial transport with a still air range of 2500 n.m. at maximum payload and a cruise Mach number of 1.15. The study resulted in an aircraft with a payload of 92,500 pounds, a gross weight of 711,478 pounds, an initial cruise altitude of 44,000 feet, a takeoff distance at maximum gross weight of 8,000 feet, and four engines, each having a static sea level thrust of 48,300 pounds. A strongly waisted fuselage, a variable sweep wing, and a delta planform horizontal stabilizer characterized the airplane design.

It is concluded that, within the framework of the limited preliminary studies conducted, the concept of a low supersonic transport appears feasible for the 2500 n.m. range.

The conclusion reached in this paper that an acoustic-type signature would probably be received on the ground if the airplane slightly exceeded the cutoff Mach number is incorrect, as shown by the results of a later investigation by Haglund and Kane (see capsule summary TM-13). It was found in that investigation that a caustic occurs at the cutoff level and only below that level does the signature decay to an acoustic wave. For a case in which the cutoff Mach number was slightly exceeded, the cutoff would occur at or below ground level.

TM-7

THRESHOLD MACH NUMBER STUDY

M. A. Coote and E. J. Kane

Boeing Company Document D6-24455-TN, October 1969

An investigation of the feasibility of airline operations in the low supersonic speed regime without producing a boom on the ground is presented in this paper. Included in the investigation are the effects of meteorological conditions, the effects of perturbations in the meteorological data, and operational systems for controlling the airplane speed to avoid the generation of sonic booms on the ground.

An envelope of airplane ground speed and Mach number was determined by considering the maximum variation in these quantities for various atmospheric models. Cutoff was achieved by insuring that the airplane ground speed was always less than the shock propagation speed at the ground. The resulting Mach number range was 1.0 to 1.326, and the resulting ground speed range was 622 knots to 675 knots.

The effects of perturbations in the meteorological data are taken into account by building safety factors into the system. The perturbations considered are wind gusts, temperature measurement errors, safe altitude effects, and temperature inversions. It is shown that allowances for wind gusts could require as much as a 20 knot reduction in ground speed. The effects of errors in the measurement of ground temperature are shown to be small, and the accuracy required is within ±1 to 2°F.

The safe altitude is the lowest altitude reached by the shock wave and the "buffer" zone between there and the ground is used to damp out the acoustic signal propagating from the shock. The safe altitude effect is approximated in this study by assuming a constant speed penalty of 10 knots. A temperature inversion is shown to be beneficial in that it is an automatic safety factor.

Several ground speed control methods are considered which will provide boom-free ground conditions. Each of the methods assumes varying degrees of complexity, the purpose of which is to expand the ground speed-Mach number envelope, thereby improving the average ground speed. The simplest system is the constant high subsonic Mach number cruise which has an average ground speed of 560 knots but suffers from a wide range in ground speed of approximately ±15%. The most complex method, an inflight planning method, combines a fully automated on-board control system with a fine mesh of automated weather stations on the ground. The method allows the ground speed to be continually varied in a smooth manner, thereby maximizing the ground speed. The average ground speed in this case was approximately 645 knots with a maximum Mach number over 1.30.

The recommended ground speed control method is an inflight planning method which combines the automated on-board system with the existing net of weather stations. The on-board speed control system is a combination of an inertial navigation system, an accurate airplane Machmeter, and a computer. Using this method, the airplane ground speed is varied in flight at certain discrete points along the ground track depending on the inputs from the ground stations. Due to the uncertainties in weather conditions between weather stations, an additional safety factor of approximately 15 knots is included. With this method the airplane must be capable of cruising efficiently over a wide range in Mach number, i.e., 0.99 to 1.3, while the variation in ground speed and, more importantly, productivity is only 6% about a mean speed of 630 knots.

There have been several other papers written concerning the feasibility of airline operations in the threshold Mach number regime (see capsule summaries TM-4, TM-6, TM-8, and TM-9). However, this investigation is the only one which considers ground speed control methods. This was also the first paper to show that the condition which insures cutoff is that the airplane ground speed be less than the propagation speed of the shock at ground level.

TM-8

A PRELIMINARY CLIMATOLOGY OF THE THRESHOLD MACH NUMBER

George T. Haglund

Boeing Company, Commercial Airplane Division, Document No. D6-23619 TN, February 1970.

This paper is essentially the same as the one described in capsule summary TM-9. However, the present paper contains appendices not included in the later paper. The present capsule summary discusses only the material contained in the appendices of this report. For a summary of the rest of the report see capsule summary TM-9.

The topics discussed in the appendices are: (1) effect of airplane heading on the threshold Mach number; (2) effect of airplane climb or descent on threshold Mach number; (3) the "improved" shock propagation speed; and (4) the possibility of sonic booms occurring during cruise slightly below Mach 1.0.

For a given wind speed profile below an airplane, as the airplane heading is changed, the threshold Mach number and ground speed change, since the headwind component changes. These effects are illustrated by computing the threshold Mach numbers and ground speeds for a number of different airplane headings at 45,000 feet for each of four model atmospheres. The results show that the variations with airplane heading are significant.

The brief discussion of the effect of airplane climb or descent on threshold Mach number is based upon the equation presented in an earlier paper by Lina and Maglieri (see capsule summary TM-2). The conclusion of this brief discussion is that operational use of the climb effect during cruise does not appear feasible.

The effect of using an "improved" shock propagation speed, which takes into account nonlinear effects, on the altitudes at which the caustic occurs for threshold Mach number flight is shown to be small. For a shock wave with an overpressure of 2.0 psf under standard sea-level no-wind conditions, the results show that the shock velocity is 0.04 percent greater than the local speed of sound, the threshold Mach number is also increased by 0.04 percent, and the caustic altitude is about 100 feet higher above the ground. It is concluded that, in most cases for weak shock waves, the use of the improved shock propagation speed in the calculation of the threshold Mach number is not justified since much larger errors are present due to inaccuracies in the measurement of the temperature and wind profiles.

The threshold Mach number equation in the form shown below, is used to investigate the possibility of sonic booms during cruise slightly below Mach 1.0.

$$M_T \cdot a_A + U_A = [a(Z) + U(Z)]_{max}$$

where M_T = threshold Mach number

a_A = sound speed at airplane altitude

U_A = wind speed at airplane altitude

and $[a_{(Z)} + U(Z)]_{max}$ = maximum value of sum of sound speed and wind component speed between airplane and ground

The left-hand side of the equation is simply the airplane ground speed and the right-hand side is the maximum shock wave propagation speed below the airplane. A sonic boom is heard on the ground when the airplane ground speed is greater than the maximum shock propagation speed. A solution to the equation exists, however, when M_T is less than 1.0. This occurs when U_A and a_A are large enough so that the airplane ground speed is equal to $[a(Z) + U(Z)]_{max}$, although M_T is less than 1.0. This can occur with a strong tailwind at the airplane, and the most favorable condition is to have a large wind gradient just below the airplane so that the energy of the pressure disturbances is formed into a shock wave close to the airplane. An order-of-magnitude estimate showed that the tailwind gradient required for shock formation is not out of the ordinary. It is pointed out, however, that true assessment of the possibility of sonic boom from slightly subsonic flight will have to wait for experimental verification.

TM-9
A PRELIMINARY CLIMATOLOGY OF THE THRESHOLD MACH NUMBER AND IMPLICATIONS FOR BOOMLESS SUPERSONIC FLIGHT
George T. Haglund
Paper Presented at the Fourth Conference on Aerospace Meteorology, Am. Meteorol. Soc. and AIAA, Las Vegas, Nevada, May 1970, pp. 399-413

The results of a preliminary attempt to specify the limits and feasibility of boomless supersonic cruise are presented in this paper. The San Francisco to New York City route is considered, and the factors investigated include the operating environment, Mach number, and ground speed of a low supersonic airplane with the restriction of no sonic boom at the ground.

The equation used for determining the threshold Mach number is the one given in capsule summary TM-3. Also, just as was done in the paper summarized in capsule summary TM-7, a 10 knot safety factor is applied to the ground speed corresponding to the threshold Mach number. The purpose of this safety factor is to assure that the caustic occurs at a high enough altitude above the ground so that the acoustic waves are sufficiently damped out before reaching the ground. Applying this safety factor results in a "safe" threshold Mach number and a "safe" ground speed.

Four cities (Oakland, Denver, Peoria, and New York City) along the San Francisco to New York route were chosen for use in investigating the variation in threshold Mach number along the route. These cities were chosen since they were the only ones for which the required meteorological data were available. In addition to the variation in safe threshold Mach number and safe ground speed from city to city, the variation in these quantities from season to season was determined.

The meteorological data for each city included almost 5000 atmospheric soundings and consisted of temperature and wind observations up to 55,000 feet. The safe threshold Mach number and safe ground speed were determined for each individual sounding. These results were then used to make a statistical analysis of the safe threshold Mach number and safe ground speed for each city and for various seasons. Included in this analysis is a computation of the route mean safe threshold Mach numbers, which were computed from a formula which weighted the safe threshold Mach numbers for each of the four cities according to the approximate amount of the flight path which was represented by the results for that city. The table below, which was taken from this paper, shows a sample of the results obtained.

Airplane Altitude = 45,000 Feet

WESTBOUND Headwind

	95% Probability of Being Greater Than	50% Probability of Being Greater Than	5% Probability of Being Greater Than
JAN	1.140	1.185	1.250
JULY	1.175	1.230	1.260
ANNUAL	1.155	1.200	1.250

EASTBOUND (Tailwind)

	95% Probability of Being Greater Than	50% Probability of Being Greater Than	5% Probability of Being Greater Than
JAN	1.020	1.050	1.090
JULY	1.060	1.110	1.155
ANNUAL	1.035	1.080	1.140

Most probable and extreme route mean safe threshold Mach numbers for San Francisco to New York City route

Airplane Altitude of 45,000 Feet

WESTBOUND (Headwind)

	95% Probability of Being Greater Than	50% Probability of Being Greater Than	5% Probability of Being Greater Than
Oakland	1.150	1.195	1.255
Denver	1.120	1.199	1.270
Peoria	1.125	1.200	1.280
N.Y.C.			
Annual	1.130	1.200	1.280
Jan.	1.120	1.180	1.280
July	1.160	1.220	1.280

MOST PROBABLE AND EXTREME SAFE THRESHOLD MACH NUMBERS AT OAKLAND, DENVER, PEORIA, AND NEW YORK CITY (ANNUAL)

The route mean safe ground speed data were used to compute block times for boomless supersonic flight over the San Francisco to New York City Route. It was found that a block time of 4.0 hours or less, compared to typical subsonic block times of about 5.2 hours, could be flown almost 100% of the time during eastbound flights and about 70% of the time for westbound flights. Very little variation of block time was found with season of year. It was found that during strong tailwind situations in winter, the threshold Mach number may be close to 1.0 but the airplane ground speed is high. It is pointed out that, for this case, it may be feasible to operate at Mach 0.95 with only a slight reduction in ground speed. A conservative block time for such flights would be about 4.3 hours, however, this concept would require a very versatile airplane Mach number capability.

The final topic considered is the effect of mesoscale meteorological variations on the safe threshold Mach number and safe ground speed. It is concluded that either an additional safety factor reduction in the allowable ground speed is needed or sophisticated instrumentation will be needed to measure the variations and to control the airplane cruise conditions accordingly to ensure that no noise occurs at the ground.

In a previous threshold Mach number study (see capsule summary TM-4), statistical atmospheric data (means and standard deviations) at only seven altitudes were used to compute average monthly and 95% probability threshold Mach numbers. It is pointed out in the present paper that such an approach gives a fairly accurate mean threshold Mach number, but it significantly underestimates the variability of the threshold Mach number. The method used in the present paper is the correct way to determine the climatology of the threshold Mach number and consists of using a large number of atmospheric soundings of temperature and wind to compute a large number of threshold Mach numbers, and then to perform the statistical analysis on the threshold Mach numbers themselves.

This is the most extensive investigation of this type that has been conducted.

TM-10

A NOTE ON THE CALCULATION OF "CUT-OFF" MACH NUMBER

J. M. Nicholls

The Meteorological Magazine, Vol. 100, No. 1183, February 1971, pp. 33-46

This paper presents a derivation of the cutoff Mach number. The resulting equation for the cutoff Mach number differs from that given earlier by Kane and Palmer (see capsule summary TM-3), and it is claimed that the earlier result is in error. However it is shown in a later note by Haglund and Kane (see capsule summary P-167) that the discrepancy in equations is due merely to the use of different coordinate systems. Both give the same results when correctly applied.

TM-11

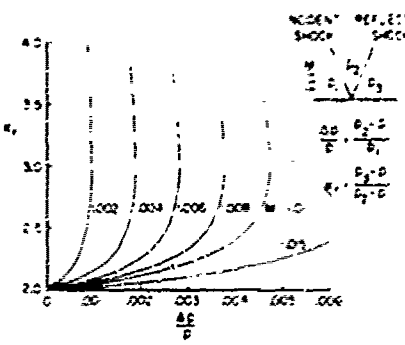
SONIC BOOM REFLECTION FACTORS FOR FLIGHT NEAR THE THRESHOLD MACH NUMBER

Charles L. Thomas

Journal of Aircraft, Vol. 8, No. 6, June 1971, p. 490

This short note discusses the reflection of a very weak shock wave off a smooth surface for the condition in which the incident shock wave is merely perpendicular to the surface. The investigation is based upon the use of oblique shock relations.

It is found that the pressure rise across the reflected shock can be up to twice the pressure rise across the incident shock. This results in reflection factors as large as three. The results are summarized in the figure below, which was taken from this paper. The figure shows that for values of $\Delta P/P$ typical of the sonic boom front shock and values of M close to one, the reflection factor can range between two and three. For any given M and $\Delta P/P$, there are two reflected shocks that are mathematically possible. The stronger solution, shown by dashed lines, does not actually occur, however. The figure also shows that there is a maximum $\Delta P/P$ for which a regular reflection is possible for each Mach number. A Mach reflection occurs if $\Delta P/P$ is larger than this maximum.



Regular reflection of a very weak shock wave from a smooth surface

It is stated by the author that the results shown in the figure were not intended to be used quantitatively in sonic boom calculations because $\Delta P/P$ cannot be estimated theoretically when the flight Mach number is very near the threshold Mach number. It is pointed out, however, that the figure does demonstrate that the sonic boom reflection factor should not be automatically assumed to be less than or equal to two, just because the sonic boom pressure wave is very weak.

The results of a later investigation by Haglund and Kane (see capsule summary TM-13) suggested that the reflection coefficient did not increase to 3.0 near cutoff but rather decreased gradually from 2.0 to 1.0, as predicted in an earlier paper by Kane and Palmer (see capsule summary TM-3).

TM-12

MEASUREMENTS OF SONIC BOOM SIGNATURES FROM FLIGHTS AT CUTOFF MACH NUMBER

Domenic J. Maglieri, David A. Hilton, Vera Huckel, and Herbert R. Henderson

NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 243-254

This paper presents a discussion of preliminary results obtained in the sonic boom flight tests conducted at Jackass Flats, Nevada. Use was made of the 1500-ft high BREN tower located at the test site to investigate the signatures resulting from flights near the cutoff Mach number.

This preliminary analysis of the data showed the following:

1. U-shape or caustic signatures resulting in overpressure enhancement were observed at the shock wave extremities, and the highest measured levels were on the order of three times the nominal N-wave overpressures associated with operations at higher supersonic Mach numbers.

2. The shock wave was found to be quite sensitive at its extremity to local atmospheric conditions.

3. Good qualitative agreement with theory was obtained regarding the extent of the subsonic, sonic, and supersonic flow fields and their associated overpressure signature shapes.

An extensive analysis of the data discussed briefly here is presented in a later paper by Haglund and Kane (see capsule summary TM-13). The reader is referred to that capsule summary for a more thorough discussion of the Jackass Flats results.

TM-13

FLIGHT TEST MEASUREMENTS AND ANALYSIS OF SONIC BOOM PHENOMENA NEAR THE SHOCK WAVE EXTREMITY

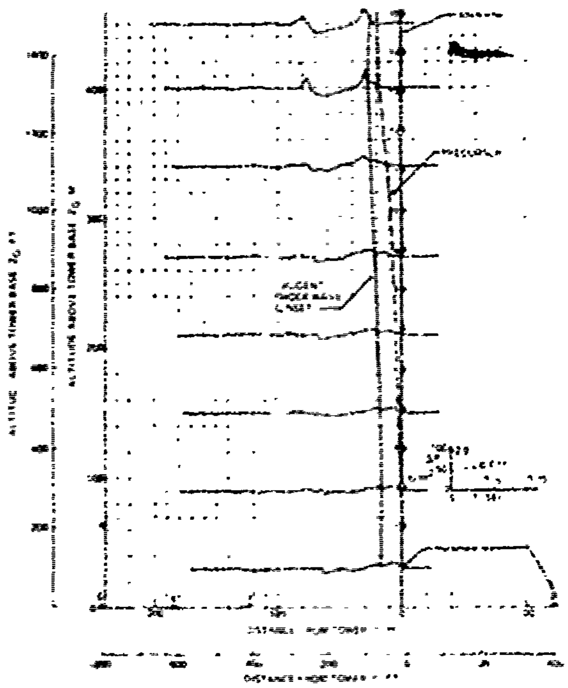
George T. Haglund and Edward J. Kane

NASA CR-2167, February 1973

The results of the sonic boom flight test program conducted at Jackass Flats, Nevada, during the summer and fall of 1970 are presented in this report. The program consisted of 121 sonic-boom-generating flights over the 1529 ft instrumented BREN tower. These flights were designed to provide information on several aspects of sonic boom, including caustics produced by steady flight near the threshold Mach number, caustics produced by longitudinal accelerations, sonic boom characteristics near lateral cutoff, and the vertical extent of shock waves attached to near-sonic (M<1.0) airplanes.

Fifteen microphones were placed at 100-ft intervals on the BREN tower. As a result, sonic boom measurements as a function of altitude were obtained for the first time. The primary goal of this test series was to obtain definitive data on caustics produced by accelerations and by atmospheric refraction (threshold Mach number and lateral cut off). The present capsule summary discusses only the portion of the report dealing with threshold Mach number flight. For a summary of the rest of the report, see capsule summary F-162.

A total of 79 threshold Mach number flights were made. Of these flights, eleven produced shock waves that were cut off on the tower, and thirty-seven produced shock waves that were cut off above the tower. The figure below, which was taken from this paper, shows a typical case in which shock wave cutoff occurred near the top of the tower. It can be seen from the figure that a caustic-like pressure signature occurred at the tower top preceded by a pressure rise, coincident with the shock wave becoming vertical to the ground. The shock waves decay rapidly with distance below the cutoff altitude, with acoustic-like disturbances occurring at the ground.



Shock wave profile and tower pressure signatures, $M \sim M_T$

The following are the most significant results found in this investigation:

1. At speeds greater than the threshold value, regular sonic booms were observed, and linear sonic boom theory was found to agree very well with observed data.

2. A characteristic of pressure signatures near the cutoff condition was that pressure pulses or "precursors" were frequently evident propagating ahead of well-defined shock waves in the pressure signature. Precursors appeared to be associated with near-sonic conditions, where disturbances generated by the shock wave can propagate ahead of it. In some cases several precursors could be seen. Friedman and Chou (see capsule summary P-) had predicted the presence of such precursors in an earlier theoretical study.

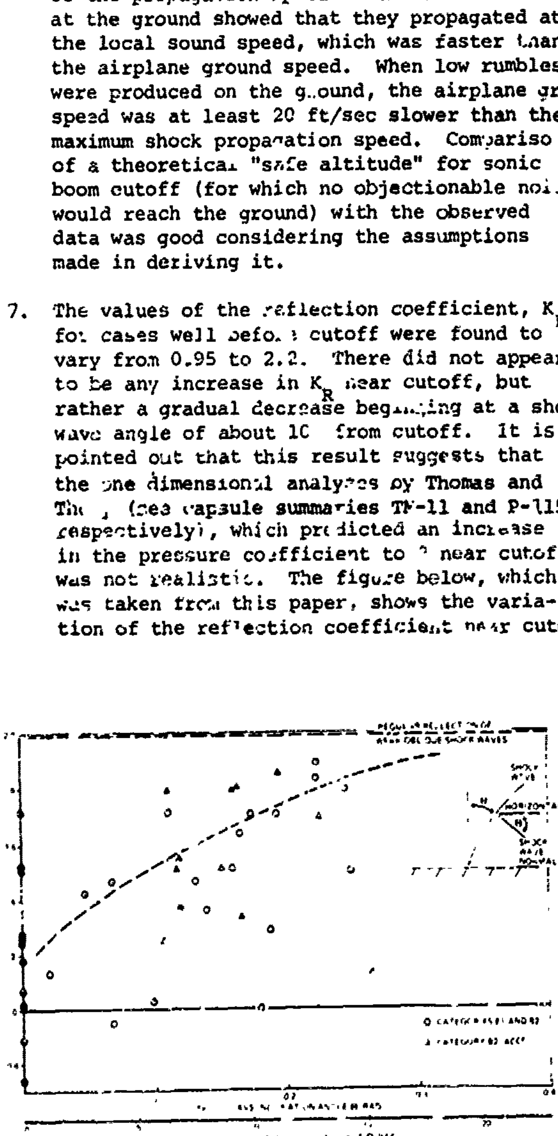
3. The flights for which the shock wave was cut off on the tower sh[illegible] that the pressure signature varied from an N-wave above cutoff level to a U-shaped caustic signature at cutoff level to an acoustic-type signature below the caustic.

4. Significant increases in overpressure were found to occur within about 300 ft above and below the caustic associated with the cutoff. However, the caustic intensities were still only about 0.5 to 1.1 psf. This was an amplification of 1 to 1.8 compared to steady, level flight. For one case, however, an overpressure of 2.82 psf was measured where very sharp peaks characteristic of signature distortions due to microscale turbulence in the pressure signature occurred.

5. Observed pressure signatures in the vicinity of caustics had a duration that was about 40% greater than pressure signatures produced at higher Mach numbers.

6. Almost half of the threshold Mach number flights produced rumbles or lower booms at the ground, since cutoff occurred above the tower. Analysis of the propagation speed of these disturbances at the ground showed that they propagated at the local sound speed, which was faster than the airplane ground speed. When low rumbles were produced on the ground, the airplane ground speed was at least 20 ft/sec slower than the maximum shock propagation speed. Compariso of a theoretical "safe altitude" for sonic boom cutoff (for which no objectionable noise would reach the ground) with the observed data was good considering the assumptions made in deriving it.

7. The values of the reflection coefficient, K_R, for cases well before cutoff were found to vary from 0.95 to 2.2. There did not appear to be any increase in K_R near cutoff, but rather a gradual decrease beginning at a shock wave angle of about 1C from cutoff. It is pointed out that this result suggests that the one dimensional analyses by Thomas and Th , (see capsule summaries TM-11 and P-115, respectively), which predicted an increase in the pressure coefficient to ? near cutoff, was not realistic. The figure below, which was taken from this paper, shows the variation of the reflection coefficient near cutoff.



Variation of ground reflection coefficient near cutoff

Prior to this investigation there had been only two cases in which flight tests were used to investigate the pressure signatures resulting from threshold Mach number flight (see capsule summaries TM-2 and TM-5). Those two test series were of excellent quality, but they were much less extensive than the present investigation. Furthermore, the use of a much higher density of microphones in conjunction with the use of the BREN tower in the present investigation enabled the vertical variation in pressure signature shape near the cutoff level to be defined, whereas this was not possible in the earlier experiments. Because of this, the results of the present investigation exemplify the present state of knowledge concerning the sonic booms produced by threshold Mach number flight.

TM-14

FURTHER ANALYSIS OF SONIC BOOM DATA MEASURED NEAR THE SHOCK WAVE EXTREMITY

George T. Haglund and Edward J. Kane

NASA CR, October 1973

This report analyzes data concerning son... characteristics near the shock wave extremity obtained during the sonic boom flight test program conducted by the NASA over the instrumented BREN tower during the summer and fall of 1970. Initial analyses of these data (see capsule summaries TM-1: and TM-13) showed that they were of sufficient quality and interest to warrant further study. This report presents the results of a more detailed study of selected flights.

A detailed analysis of the transonic flight test data indicated that the prevailing meteorological conditions influence the vertical extent of attached shock waves produced during near-sonic flight. At Mach 0.98 the lower extremity of the shock wave on one flight extended to 1600 ft. beneath the airplane, while under different meteorological conditions it extended to only about 560 ft. It was found that the airplane Mach number had a direct influence on the vertical extent of attached shock waves; for airplane Mach numbers less than 0.98 the shock waves probably did not extend much more than 300 ft. beneath the airplane. It is hypothesized that the extension of attached shock waves to lower altitudes may explain several "accidental" sonic booms produced by low-altitude, marginally subsonic airplanes (although Machmeter errors may also be responsible). It is pointed out that this phenomenon should be considered for transport airplanes designed to cruise at Mach 0.98. One flight conducted at Mach 1.05 produced near-field pressure signatures that compared favorably with theoretical results.

A theoretical safe altitude for sonic boom cutoff during threshold Mach number flight was shown to be valid within experimental accuracy over a wide range of meteorological conditions. As a result, it is concluded that it should be possible to estimate reasonably well the buffer zone depth (or ground speed reduction) for any airplane and meteorological condition. For cutoff at or above the safe altitude, average maximum free-air overpressures of the pressure waves were less than 0.2 psf. In some cases very low intensity

acoustic waves propagated to the ground even though cutoff apparently occurred several kilometers above the ground. Pressure signatures in the vicinity of the caustic exhibit the U-wave rather than the N-wave shape. Below cutoff, rounded, low-magnitude acoustic waves occurred. Comparison of a recent theoretical method (see capsule summary M-62) for calculating the acoustic pressure waves below the threshold Mach number caustic showed excellent agreement with observation near the caustic, but predicted overpressure levels significantly lower than observed far from the caustic. Various operational aspects of threshold Mach number operation were considered and problem areas were discussed. These included the use of airplane ground speed for speed specification (instead of Mach number), various meteorological effects, airplane systems, and recommendations for calculating the speed safety factor.

The analysis of caustics produced by low-magnitude accelerations during flight at Mach numbers slightly greater than the threshold Mach number showed that folds and associated caustics were produced by slight changes in the airplane ground speed. In several cases it was possible to correlate the airplane acceleration magnitude with the measured caustic on the tower. These results indicated an increase in caustic intensity with increasing acceleration. Caustic intensities ranged from 1 to 3 times the nominal steady, level flight intensity. The wave folding produced by airplane ground speed changes explained the observed multiple shock waves on the BREN tower for the cases considered and tended to verify recent theoretical work which has shown that wave folding occurs for weak shocks (see capsule summary P-161).

The analysis of caustics produced by longitudinal accelerations showed that, for these cases, acceleration magnitude appears to have an effect on the caustic intensity. Calculated theoretical shock wave profiles agreed reasonably well with the observed shock wave locations and helped to illustrate the focusing effect near caustics. The observed pressure signatures are documented in detail.

In conjunction with the analysis of the experimental data, methods to alleviate the caustic produced during the transonic phase of flight were considered. It was found that low-magnitude acceleration may provide some alleviation of caustic intensity. The limited experimental data suggested an amplification of about 2 for an acceleration magnitude of about 0.3 m/sec^2 (1.0 ft/sec^2). In addition, a maneuver designed to eliminate the transonic acceleration caustic was investigated. Although the maneuver showed promise, it was concluded that further study is needed to determine its feasibility for commercial SST operation.

To obtain further measurements near the shock wave extremity, additional threshold Mach number flights, additional longitudinal acceleration flights at varying accelerations, and additional transonic flights are recommended as well as a series of flights to measure the effects of thermal and dynamic atmospheric turbulence. It is recommended that these flights be conducted under stable atmospheric conditions (except for turbulence tests), using a test airplane with an inertial navigation system. Use of the instrumented BREN tower or a similar facility, with microphones mounted on reflecting boards at several locations on the tower adjacent to free-air microphones, is recommended.

The portion of this investigation dealing with the attached shock waves generated by aircraft flying at high-subsonic speeds was the first of that type to be conducted.

9.0 SIMULATION METHODS

SM-1
LABORATORY TESTS OF SUBJECTIVE REACTIONS TO SONIC BOOM
K. S. Pearsons and K. D. Kryter
NASA CR-187, March 1965

In the investigation described in this report, subjects compared, in a special laboratory chamber, the subjective acceptability or noisiness of sonic booms and subsonic jet aircraft noise. Only the simulation facility used in this experiment will be described here. For a summary of the results of the investigation see capsule summary HRSC-10.

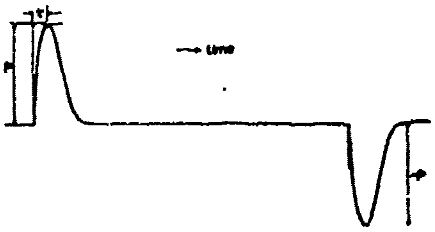
The sonic boom simulation facility used in this experiment consisted of a 3.5 ft x 3.5 ft x 7.9 ft high room constructed of 8-inch solid concrete block. Five 18-inch loudspeakers with center-tapped voice coils mounted in the walls and ceiling were used to produce the peak pressure associated with a sonic boom. The type of sonic boom that is generally observed outdoors was generated by means of a waveform generator called a "photoformer." This device, generated an electrical waveform by following a silhouette placed in the photoform. The electrical waveform was then converted into a pressure waveform by the loudspeakers. Indoor-type sonic booms, because of their greater complexity were obtained from FM tape recordings made inside a house under the flight path of a jet aircraft flying at supersonic speed.

This facility was better as a simulator of outdoor-type sonic booms than indoor types because the simulated indoor sonic booms lacked the vibrational component associated with actual indoor sonic booms which results from structural vibration.

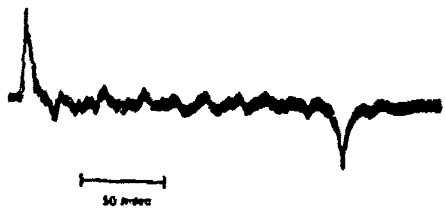
SM-2
SONIC BANG SIMULATION BY A NEW EXPLOSIVES TECHNIQUE
S. J. Hawkins, J. A. Hicks
Nature, Vol. 211, No. 5055, Sept. 17, 1966, pp. 1244-1245

This short article describes an explosives technique for simulating sonic booms. This technique uses line charges and is based upon the fact that an extended explosive charge must give rise to a pressure waveform the duration of which--whatever its shape--is approximately its line-of-sight extension di[illegible] the average air shock velocity across th[illegible]ion. For charges of small weight the air shock rapidly decays to sonic velocity and because of this a distant observer experiences a pressure wave the duration of which in milliseconds is roughly equal to the extension in feet--the shape is governed by the distribution of explosive along the extension.

The extended charge is considered as a spatial array of infinitesimal point charges detonated simultaneously, the combined effects of which are approximated by the assumption of linear superposition. An integral expression is then derived for the pressure waveform in terms of the explosive mass, observation distance, time, charge distribution, and time for the wavefront to reach the observer. The waveform given by this equation for the simple case of a uniform straight linear charge observed from a distant point on the axis is shown in the first figure below, which was taken from this paper. The second figure, which was also taken from this paper, shows the actual waveform generated by such a charge distribution. It can be seen that the agreement between the two is fairly good.

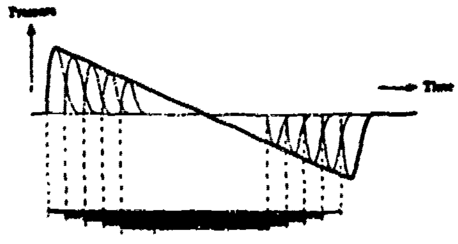


Calculated wave form

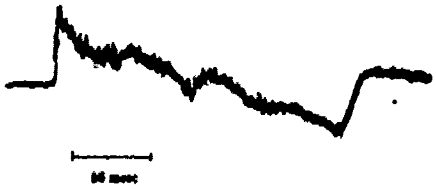


Experimental wave form

It is then shown that many complex waveforms can be synthesized by detonating linear charges constructed from multiple strands of detonating fuse of different lengths. The first figure below illustrates the underlying principle and the second figure shows an experimentally observed waveform generated in such a manner.



Principle of N-wave synthesis from uniform linear charges



Experimental wave form

The differences between the waveforms generated using this technique and an actual sonic boom waveform, such as energy spectra, rise time, and peak overpressure are then discussed briefly. It is concluded that the energy spectra of the simulated and actual N-waves agree well in the frequency range below about 100 Hz but diverge toward higher frequencies, this divergence being partly a result of the different noise

contents of the waveforms and partly because of the different pressure rise rates of the shock fronts. Thus this type of simulant would be acceptable for studies of structural response but may not be adequate for human response studies.

SM-3
A FEASIBILITY INVESTIGATION CONCERNING THE SIMULATION OF SONIC BOOM BY BALLISTIC MODELS
J. G. Callaghan
NASA CR-603, Oct. 1966

The results of a series of tests conducted to determine the feasibility of using ballistic models to provide laboratory simulation of sonic boom are presented in this report. The test program consisted of two main parts: (1) the determination of appropriate instrumentation to measure the pressure signature of small-scale, rapidly moving ballistic models (see capsule summary IT-7), and (2) the definition of problems associated with launching winged ballistic models.

The testing of winged models consisted of determining the type of flight path obtainable in a ballistic range at launch Mach numbers of about 3.0, and defining the fabrication problems associated with such models. The results of these tests indicated the following:

1. Motion of delta wing ballistic models varied from a smooth type of flight to one of highly erratic oscillatory motion. Consideration of model tolerances, sabot design, and light-gas gun tolerances revealed no significant parameters which would lead to the allowance of any degree of repeatability of model flight path. On those tests wherein model motion was of a nonoscillatory type, good shock wave pressure signatures were obtained.

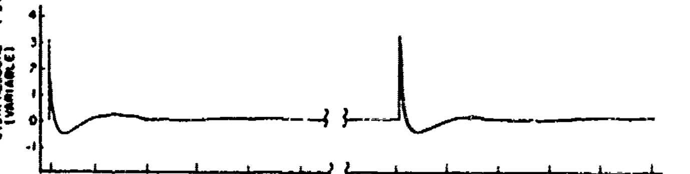
2. Models launched into the ballistic range tank at reduced pressures exhibited a more acceptable type of motion.

3. Limited testing was conducted to explore the possibility of launching bodies of revolution at Mach numbers up to 5. Good quality pressure signatures were obtained.

Ballistic range techniques have been used in various investigations (Kane in capsule summary G-14, Bauer and Bagley in capsule summary P-113, and Collins in capsule summary G-80, for example). However, all of these tests involved projectiles that were bodies of revolution. The present paper was the first to investigate the possibility of using winged ballistic models.

SM-4
SONIC BOOM SIMULATION USING SHOCK TUBE TECHNIQUES
H. E. Pahlke, G. T. Kantarges, and J. J. Van Houten
LTV Research Center Technical Report 0-71200/7TR-117, March 1967

This report describes a device developed for simulating sonic booms. The basic system consists of a combination of two conventional shock tubes and a large exponential acoustic horn coupled to the end of the shock tubes for the development of shock waves approximating those associated with sonic boom phenomena. This device generates two shock fronts with a variable time delay, resulting in a simulated sonic boom of the form shown below. It is shown that overpressures well above 20 psf can be achieved over a fairly large area around the exit of the horn.



Pressure signatures produced with the sonic boom simulator

The utility of the simulated sonic booms is based on the finding by Zepler and Harel (see capsule summary HRSC-16) that when an N-wave impinges upon the human ear loudness is determined by the two pressure pulses while low frequencies below 50 Hz are not important in the subjective analysis. Thus the device may be useful in investigating human response to sonic booms. Its utility for investigating structural response to sonic booms is very limited, however.

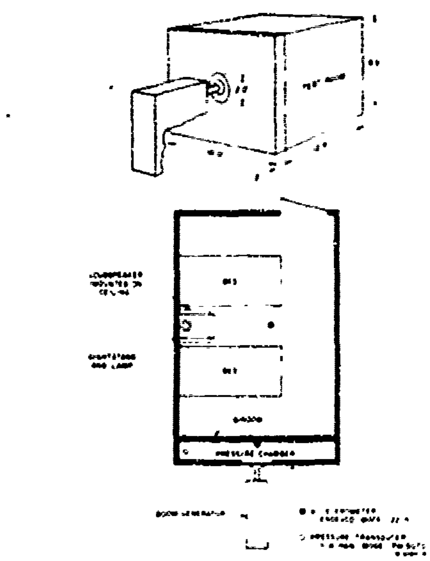
SM-5
A PRELIMINARY STUDY OF THE AWAKENING AND STARTLE EFFECTS OF SIMULATED SONIC BOOMS
Jerome S. Lukas and Karl D. Kryter
NASA CR-1193, September 1968

This report presents a description of the development of the indoor sonic boom simulator developed at Stanford Research Institute and the results of preliminary experiments concerned with the effects of sonic booms from this simulator on sleep and startle. Only the description of the simulator will be summarized here. For a summary of the results of the experiments see capsule summary HRSC-40.

The sonic boom simulator described in this report consisted of an airtight pressure chamber, having the internal appearance of a typical residential bedroom, whose walls were of standard construction: drywall on 2" x 4" studs, 16" on center. In contrast, the outside walls of the pressure chamber were constructed of 3/4" plywood mounted on 2" x 4" studs, 12" on center, with horizontal cross supports joining adjacent studs about 3' from either end of the stud.

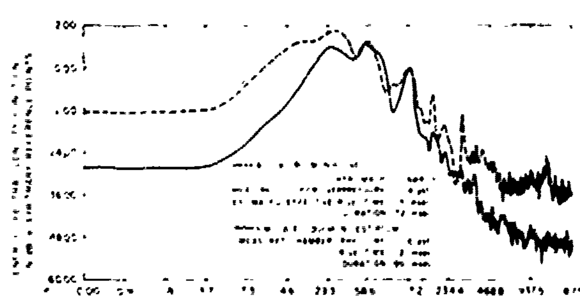
In order to simulate both the acoustic and vibrational components of an indoor sonic boom, the best approach appeared to be the loading of one wall of the room with an N-wave. Thus an electromechanical device was designed and built to generate an N-wave of pressure into a hermetically-sealed chamber. One wall of the pressure chamber also formed one wall of the experimental test room. The figure below, which was taken from this paper, shows a sche-

matic of the facility.



Schematic of sonic boom study facility

In testing the performance of this simulator (see figure below), a consistent difference of about 12 dB at frequencies above 250 Hz was found due to a somewhat slower rise time of the simulated sonic boom in comparison to booms produced by actual aircraft. It is stated that this difference between the simulated and actual sonic booms tends to make the simulated boom have a slightly less sharp "crack" than the typical indoor sonic boom. However, it is also stated that these frequencies contributed relatively little to the energy spectra of either simulated or actual booms.



Indoor spectral energy functions of actual and simulated booms

This type of sonic boom simulation facility is the best method yet developed for simulating indoor sonic booms, since it simulates both the acoustic and vibratory characteristics of indoor sonic booms. This facility was used in numerous later investigations (see capsule summaries HRSC-51, HRSC-53, HRSC-67, and HRSC-68).

SM-6
RELATIVE ANNOYANCE AND LOUDNESS JUDGEMENTS OF VARIOUS SIMULATED SONIC BOOM WAVEFORMS
L. J. Shepherd and W. W. Sutherland
NASA CR-1192, September 1968

The results of a series of investigations, initiated in an effort to assess the effect of sonic boom signature modification on human subjective response, are presented in this paper. The investigation was conducted using Lockheed's sonic boom simulation facility. Only the simulation facility is described here. For a discussion of the results of the investigations, see capsule summary HRSC-41.

The simulator used in this investigation consisted of an airtight chamber having dimensions of 41 x 42 x 72 inches (inside dimensions) giving a volume of 70 cu. ft. Two of the chamber walls were solid concrete block and the other two were 1-inch plywood stiffened by steel angles. The plywood walls contained the variable volume elements (loudspeakers) which were used to produce the desired pressure-time variation and one was hinged to serve as a door.

The desired pressure-time variation was provided on one channel of an FM tape. The test signatures were recorded by a separate FM system. Simple theoretical shapes containing only straight line elements were generated by an analogue-relay type signal generation; more complicated typical flight signatures were transcribed from oscillograph records through use of an optical following system.

It is shown that a relatively wide range of outdoor sonic boom pressure signatures having peak overpressures up to about 4 psf and rise times as small as 0.002 seconds can be consistently produced in the chamber. The types of signatures successfully reproduced included N-waves, sawtooth-type signatures, flat-top signatures of the type produced at the design condition by a configuration having a three-halves power total equivalent area distribution, and an atmospherically distorted signature.

Experienced observers reported that the pressure signatures sounded like sonic booms. Preliminary results for several subjects indicated that with identical standard and compared signature shapes, the scale factor for equal loudness could be consistently set to unity within 1 dB.

This was an excellent facility for simulating outdoor-type sonic booms.

SM-7
SONIC BOOM SIMULATION FACILITIES
I. Schwartz
AGARD Conference Proceedings No. 42, Aircraft Engine Noise and Sonic Boom, May 1969, pp. 29-1 thru 29-18

This paper contains brief descriptions of the main design features of the various sonic boom simulation facilities that have been developed.

Included in the discussion are the following simulation techniques: (1) wind tunnel technique; (2) shock tube-bursting diaphragm technique; (3) ballistic range technique; (4) piston speaker technique; and (5) quick action valve-shock tube technique.

Wind tunnel testing techniques are used to extend the basic understanding of sonic boom phenomena and to establish the sonic boom characteristics of specific airplane configurations. It is pointed out that these facilities cannot produce the traveling wave or time varying wave of the actual boom, which is very important for response studies.

A shock tube-bursting diaphragm sonic boom simulation facility was developed by Ling-Temco Vought. This facility utilizes a system of shock tubes and acoustic horn to produce acoustic waves (for a more complete description of this facility, the reader is referred to capsule summary SM-4). This simulator can produce double blast waves with a maximum peak pressure of 27 psf at ten feet from the horn. The boom duration can be varied from 10 to 600 msec. The pressure signatures generated by this process have potential application to studies of human response to sonic booms, but, due to a deficiency in low-frequency content, application to studies of structural response is limited.

The ballistic range technique uses a ballistic range with a ballistic model for exploring atmospheric and topographical effects. This system produces a traveling wave and the wave shape can be varied by modifying the shape of the projectile. There are advantages for conducting simulation experiments of atmosphere dynamic effects and topographical effects on sonic booms in this type of facility, namely: (1) the simulated atmospheric dynamics, such as turbulence and temperature gradients can be prepared in a region before the projectile passes through this region; and (2) transient phenomena, such as reflection, refraction, and scattering processes can be investigated directly under most complex conditions. It is pointed out, however, that preliminary reports indicated that it is difficult to vary the shape, velocity amplitude, and rise time of the signature in a systematic manner in this type of facility.

The piston speaker technique uses a system of acoustic drivers to regulate the pressure in a chamber. The example of this type of facility that is discussed is the NASA Langley Low Frequency Noise Facility. The principal features of this facility are a cylindrical test chamber, a large piston in one end of the chamber, and a movable wall which can be positioned to close the opposite end of the test chamber. The piston is hydraulically driven to generate sound pressures. The size of the facility is sufficient to accommodate a small building structure. The overall dimensions are 30 ft long x 27 ft in diameter. Useful ranges of overpressure, rise time, wavelength, and impulse for N-wave type disturbances can be simulated in this facility. This facility is particularly well suited for studying the response of structural components. This type of facility is also amenable to a program of subjective studies relating to the indoor sonic boom exposure situation for which building vibrations are believed to be important. It cannot, however, simulate the traveling wave nature of the boom.

The last type of simulation facility discussed is the quick action valve-shock tube technique. The example of this type of facility discussed in this paper is the GASL/NASA sonic boom simulation facility. The basic concept involved in this simulator is that a pressure wave can be generated in a pyramidal duct which is proportional to the rate of change of mass flow at the sonic throat located at the apex of the pyramid (for a more complete discussion of this simulator the reader is referred to capsule summary P-127). This device concept produces an accurate traveling pressure wave, and the wave can be either scaled or full scale wavelength, depending on the size and design of the device. The ranges of performance available with this simulator are shown in the table below, which was taken from this paper.

Peak Pressure Level	up to 100 psf (48×10^3 dyns/cm^2)
Wavelength	¼ ft - 500 ft (.08 M - 152 M)
Period	300μ sec - 0.5 sec
Rise Time (minimum)	1 millisecond
Repetition Rate (typical)	up to 60/hr
Model Scale	1:1 to 1000:1
Maximum Test Station Area	8 feet square (2.4 M square)

GASL/NASA simulator capability

It is concluded that the GASL/NASA facility represents the most advanced state of the art in sonic boom simulation. It meets most of the requirements for performing basic and applied research on sonic boom phenomena including human and structural response.

This is an excellent summary of the sonic boom simulation facilities that had been developed as of 1969. Its only deficiency is that it doesn't discuss the loudspeaker-airtight chamber type facilities (see capsule summary SM-6, for example).

SM-8
THE SIMULATION OF SONIC BANGS
C. H. E. Warren
AGARD Conference Proceedings No. 42, Aircraft Engine Noise and Sonic Boom, May 1969, pp. 28-1 thru 28-13

This paper describes the various methods for simulating sonic booms which have been developed in the United Kingdom. These include explosive point charges, explosive line charges, and a shock tube device.

A single explosive point charge is shown to be a poor sonic boom simulant. Also, when experienced outdoors, it was found that a pair of explosive bangs is readily distinguished from a sonic boom. However, when experienced indoors, the pair of explosive bangs was found to be indistinguishable from a sonic boom.

A uniform explosive line charge, when experienced end-on, has been found to give a waveform consisting of single positive and negative pulses separated in time by an interval essentially equal to the length of time it takes for sound to travel the length of the charge. By superposition line charges can be built up to yield, in principle, roughly any desired waveform. It is shown that various arrangements of explosive line charges are useful tools for field studies on real buildings and for field studies on human and animal communities.

The shock tube device discussed was called the Blunderbuss. This device consisted of a conical tube having a diaphragm corresponding to the surface of a sphere having its center at the apex of the cone. The magnitude of the pressure rise at any station down the tube is governed by the pressure at which the diaphragm is burst. A pilot Blunderbuss was constructed with the diaphragm at various positions from 0.1 to 5.5 m from the apex, so that the interval between shocks of the resulting waveform ranged from about 0.6 to 3.5 ms. A good N-wave was obtained, there being two clearly defined shocks of closely equal pressure rise, a high pressure rise rate, and very little superimposed random noise. It was felt that this device could be used for a wide range of studies on human and animal subjects, and on elements of building structures.

This is a good summary of the sonic boom simulation devices that have been developed in Great Britain. For a summary of sonic boom simulation facilities developed in the United States see capsule summaries SM-7 and SM-13.

SM-9
RESEARCH AND DEVELOPMENT OF A SONIC BOOM SIMULATION DEVICE
Roger Tomboulian
NASA CR-1378, July 1969

This paper describes the development of the NASA/GASL sonic boom simulation facility. For a description of this facility the reader is referred to capsule summary P-127.

SM-10
ENGINEERING ANALYSIS AND DESIGN OF A MECHANISM TO SIMULATE A SONIC BOOM
Robin F. Barrett and Lawrence W. Redman
NASA CR-111839, August 1970

The sonic boom simulation facility described in this report is also described in a later updated report by Rash, Barrett, and Hart (see capsule summary SM-15). The reader is referred to the capsule summary of that report for a description of this simulator.

SM-11
DESCRIPTION AND CAPABILITIES OF A TRAVELING WAVE SONIC BOOM SIMULATOR
Roger Tomboulian and William Peschke
NASA CR-1696, November 1970

The purpose of the study described in this paper was to gain a more complete understanding of the performance capability of the NASA/GASL (General Applied Science Laboratories) traveling wave type sonic boom simulator, to improve its performance range and capability, and to develop test data useful for the development of larger versions of the simulator.

The facility consists of three major components. Basically, they are a conical duct, a mass flow control valve (including an air supply system) which is coupled to the duct at its apex, and a moving absorber installed at the large end of the duct. At any given instant of time during valve operation, the flow is supersonic downstream of the throat. A shock interface is found at a given location within the duct where the flow becomes subsonic. The position of the shock interface moves in the duct as a function of the mass flow. For a more detailed description of the facility the reader is referred to capsule summary P-127.

The specific areas of investigation of the present study were concerned with:

1. A study of methods and techniques to alleviate the jet noise produced during operation of the facility.

2. An extended exploration of the operating range of the simulator including study of the facility performance characteristics at various test section locations within the simulator.

3. An examination of methods for the development of non-idealized wave shapes.

4. A review of absorber materials and absorber installation techniques to improve the reflected-wave cancellation characteristics of the facility.

In addition to these areas, a diaphragm driver technique was developed for the production of fast rise time, short duration N-wave signatures, appropriate for reduced time scale experimentation.

The following conclusions were reached concerning the performance of the NASA/GASL sonic boom simulator:

1. The major effort was concentrated on the investigation of techniques for the reduction of the jet noise which accompany wave generation. The result of this effort was a demonstrated reduction of the jet noise amplitude from a minimum of 100% of the incident wave overpressure to a maximum of 25% of the overpressure. The results of the absorber investigation included a 90% attenuation of the high frequency component of the wave. The original level of attenuation of the reflected wave overpressure was approximately 67%.

2. Test data acquired during the program demonstrated the feasibility of obtaining non-normal (peaked or rounded) sonic boom signatures. The primary method used to achieve non-normal signatures, involves programming of the valve nozzle entrance shape and/or valve pintle displacement history.

3. A second method which was tested involved the use of adjustable reflective surfaces to provide a reflected wave "test" signature. This technique, which requires some additional investigation did provide satisfac-

tory results and can be used to supplement the simulator wave generating capability.

4. The investigation of the operating range and a survey of the facility provided performance data concerning the wave duration, maximum overpressures, and rise times obtainable with the facility. These performance characteristics are as follows:

	Diaphragm Mode	Valve Mode
N-wave duration (msec)	1.5 - 15	20 - 200
Overpressure (psf)	Up to 6	Up to 13.5
Min.Rise Time (msec)	.01	1
Duty Cycle (per minute)	1	1

In an earlier report (see capsule summary SM-9) Tomboulian described the research studies which were conducted to establish the feasibility, design techniques and approaches followed in the development of this sonic boom simulation facility.

SM-12
THE DEVELOPMENT OF A SONIC BOOM SIMULATOR WITH DETONABLE GASES
R. T. Strugielski, L. E. Fugelso, L. B. Holmes, W. J. Byrne
Report by General American Research Division, Niles, Illinois, GARD Project 1494, April 1971

This report describes the program conducted by the General American Research Division in cooperation with the NASA to develop a method whereby pressure signatures generated by supersonic aircraft may be readily and economically simulated with detonable gas explosions. Program efforts were directed towards two primary objectives: 1) formulation of a rational basis which enables the design of experiments which will produce a desired pressure signature, and 2) demonstration of the simulation of this pressure signal.

The method developed involved the detonation of a methane-oxygen mixture in the molar ratio of one to two contained in a slender, shaped mylar envelope. The detonation of the gas mixture was initiated by a single Primacord strand running the length of the balloon. The balloon configuration required to obtain N-waves having durations on the order of 75 milliseconds at a range of 800 feet was found to be a composite shape, 60 feet long, consisting of two truncated cones and a cylindrical segment, the cones abutting either end of the cylinder. The cone section toward the observation point deviated only slightly from a cylindrical segment, while the other cone had a greater slope. The balloon, after being filled with the detonable gas mixture, was suspended from a cable and tethered in a horizontal position 20 feet above the ground. The Primacord, necessary for stablization of the resulting pressure signal, was ignited by a conventional detonator at the end of the balloon nearest to the observation point such that the ensuing Primacord detonation propagates away from the observation point.

Signal durations of up to 75 milliseconds were recorded at distances less than 800 feet from the point of balloon detonation. Peak overpressures in the range 3 to 15 psf were obtained.

It is pointed out by the authors that the method is similar in concept to a multiple strand Primacord technique developed by Hawkins and Hicks (see capsule summary SR-48), and has a signal which is characteristically devoid of high frequency noise or "hash," typical of air shocks generated by solid explosives.

SM-13
REVIEW OF SONIC BOOM SIMULATION DEVICES AND TECHNIQUES
Philip M. Edge, Jr., and Harvey H. Hubbard
Sonic Boom Symposium, Vol. 51, No. 2 (Part 3), February 1972, pp. 722-728

This paper presents a review of the various sonic boom simulation devices and techniques that have been developed. The types of simulators discussed are shown in the table below, which was taken from this paper. This table also summarizes the type of research for which each of the simulators is best suited.

SIMULATOR CATEGORIES	RESEARCH APPLICATIONS		
	GENERATION	PROPAGATION	RESPONSE
WIND TUNNELS	✓	✓	
BALLISTIC RANGES	✓	✓	
SPARK DISCHARGE		✓	
LOUDSPEAKERS			✓
PISTON SYSTEMS			✓
SHOCK TUBES		✓	✓
EXPLOSIVES		✓	✓
AIR MODULATOR VALVES		✓	✓

Categories of sonic boom simulators and their research application

The following are the basic points brought out in this paper with regard to each of these simulators:

1. Wind tunnel testing techniques:

   These techniques are applicable in sonic boom generation and propagation research. Special models, mountings, and pressure sensors are required. One of the most important uses of the wind tunnel is to determine the sonic boom characteristics of simplified research models of basic aerodynamic shapes and of specific airplane configurations.

2. Ballistic ranges:

   This technique is also useful in sonic boom generation and propagation research. It involves the firing of a projectile model along a given trajectory through a controlled environment. This technique was used by Bauer and Bagley (see capsule summary P-113, to investiage topographic and atmospheric effects on sonic boom propagation.

3. Spark discharge systems:

   This technique has application in studying sonic boom propagation phenomena. The system consists basically of a pair of electrodes connected to a high-voltage power source. A pressure pulse representative of a miniature sonic boom is generated by the discharge across the electrode tips. This simulator has advantages in small-scale laboratory bench-type sonic boom experiments because it is relatively inexpensive to construct and operate. This type of simulator has been used by Beasley, et al (see capsule summary P-102) to investigate N-wave focusing, by Brooks, et al (see capsule summary P-112)

to investigate diffraction and reflection of sonic boom by buildings, and by Davy and Blackstock (see capsule summary P-122) to investigate the effects of atmospheric inhomogenities on sonic boom propagation.

4. Loudspeakers:

These techniques are useful in studying human response to sonic booms. They include the use of small testing chambers and special headsets. Headsets were used by Zepler and Harel (see capsule summary HRSC-16) to investigate the loudness of sonic booms. Requirements for the headset included particular attention to the fit of the earphones and special loudspeakers having flat frequency response in a range from a few cycles to about 1000 Hz. The whole-body exposure effects which may be important for some subjective studies are missing in this type of stimulation. This deficiency has been overcome by the use of small chambers equipped with loudspeaker systems. The chamber is usually shaped like a telephone booth and has loudspeakers mounted in the walls to produce N-type pressure signatures. A chamber of this type of use by Pearsons and Kryter (see capsule summary HRSC-10) to investigate subjective reactions to sonic booms. A similar device designed by Lockheed was used by Shepherd and Sutherland (see capsule summary SM-6) to determine the relative annoyance and loudness judgements of various sonic boom waveforms. The Lockheed simulator used direct amplification and frequency compensation techniques which resulted in excellent control of the overall wave shapes, rise times, and durations of the pressure stimuli. Durations in the range 100 - 500 msec, overpressures in the range 0.5 - 5.01 psf, rise times of 1 - 50 msec, and a wide variety of fine-structure detail were simulated for test purposes.

5. Piston systems:

This type of device has use in studies of human and structural response. The NASA Langley Research center low-frequency noise facility is of this type. This facility consists of a cylindrical test chamber, a 14-ft-diameter piston, and a movable wall which can be positioned to close the opposite end of the test chamber. Pressure signatures having a range of overpressures from 0.5 to 20 psf, durations from 100 to 500 msec, and rise times on the order of 120 msec can be generated by this facility. The rise times and the fine structures of the wave are not controlled variables. Lukas and Kryter (see capsule summaries HRSC-40 and HRSC-53) used a sonic boom simulator of the piston type to investigate the awakening and startle effects of sonic booms.

6. Shock-tube driven systems:

These systems are useful in propagation and response studies. A device of this type called the "Blunderbuss" was developed at the British Royal Aircraft Establishment. It consists of a conical horn having a driver section containing compressed air, a rupture diaphragm, and a driven section where the testing is accomplished. N-type signatures with overpressures up to 20 psf can be generated. Ling Temco Vought developed a simulator consisting of twin shock tube driven sections connected into a horn 13 ft. in diameter and 13 ft. in length (see capsule summary SM-4). This device does not produce an N-type signature. The signature consists of two short duration pulses which occur at predetermined time intervals to represent any given value of duration.

7. Explosive charge:

This type of simulation is most appropriate for large-scale outdoor environmental testing of building structures. Pulse type pressure signatures can be generated by exploding multiple charges at given time intervals or line charges can be arranged to produce N-type pressure signatures having a range of overpressures and durations. Another simulator of this type that has been developed involves the explosion of a cigar-shaped balloon filled with detonable gases (see capsule summary SM-12). The N-type signatures generated by this type of device have less fine-structure distortion than those from the multiple-line charges.

8. Air Modulator Valve Systems:

These systems are useful in structural response studies. A device of this type was developed by Wyle Laboratories for use in studies of glass breakage (see capsule summary SR-64). General Applied Science Laboratory (GASL) also developed a simulator of this type (see capsule summary SR-85). The GASL/NASA simulator has three major components: a specially developed high-speed flow valve, a 100-ft-long conical duct which contains the test section, and a moving absorber which serves as an acoustic termination for the duct. With this device overpressures from about 0.5 to 10 lb/ft^2 and durations from about 50 to 500 msec are obtainable. This device is advantageous in studies involving repeated load testing of structures to study their fatigue life and crack growth properties, since it can be readily operated with only a short interval between booms.

This is an excellent paper. There have been other similar reviews that have been written (see capsule summaries SM-7 and SM-8), but neither of those were as extensive and complete as the present paper.

SM-14

SONIC BOOM EXPOSURE EFFECTS II.6: SONIC BOOM GENERATORS

C. H. E. Warren

Journal of Sound and Vibration, Vol. 20, February 22, 1972, pp. 535-539

The purpose of this report is to review the facilities that exist for studying the effects of sonic booms, to discuss the types of study for which they are suitable, and to enumerate the characteristics that the facilities must have in order that

meaningful and relevant experiments may be performed.

The sonic boom generation and simulation devices and facilities discussed include: (1) ordinary military flying; (2) special test flights; (3) explosive charges; (4) acoustic guns; (5) traveling wave devices; and (6) speakers, pistons, and other acoustic devices. The following are the main points brought out in conjunction with each of these areas:

1. A certain amount of information can be obtained in regard to the effects of a series of sonic booms on multitudes of objects by studying the effects produced by ordinary military supersonic flying. The advantage of such studies is that the objects themselves are usually in their normal and natural environment.

2. Booms of the overpressure and signature interval typical of possible commercial supersonic aircraft can be obtained by special test flights of their prototypes. However, this does not allow the habituation of people nor the structural damage due to fatigue to be studied.

3. The simulator employing a line charge of explosives developed by Hawkins and Hicks (see capsule summary SR-48) is suitable only when the responses at frequencies below 100 Hz are of most interest, such as studies on building structures, or when those frequencies are most contributory, such as studies on persons inside buildings, since there tends to be an excess of energy at frequencies above about 100 Hz. Another shortcoming of this simulator is the difficulty of making the angle of incidence on a building representative of that of actual sonic booms. On the other hand, the general boom overpressure and signature interval can be controlled and varied at will.

4. "Acoustic gun" is a term that is used to describe various simulators developed in different countries. Their common feature is some form of boom-producing tube aimed at the object to be exposed. This type of simulator can simulate the boom peak overpressure and the high frequency content of a sonic boom N-wave, and, possibly the rise time. On the other hand, it completely lacks the low-frequency content associated with the large impulse of a sonic boom.

5. In traveling wave devices (see capsule summary SM-11, for example) the bursting of a diaphragm causes an acoustic signal having the form of an ideal sonic boom N-wave to travel down a tube to a test area of some 3 m square. Such a simulator is suitable for experiments requiring typical, simple, highly controllable and repeatable sonic booms. Because high intensity sonic booms can easily be produced, this simulator is very suitable for determining threshold levels above which specific effects on objects occur, thereby yielding the safety margin.

6. The simulated sonic booms produced by an array of loudspeakers mounted in the walls of a pressure booth (see capsule summary HRSC-41) are suitable mainly for psychoacoustic experiments, since only auditory cues are simulated.

7. Simulated booms obtained by replaying recordings of sonic booms through loudspeakers in an ordinary room can produce the auditory stimuli of indoor-recorded sonic booms, which do not contain shock waves. It cannot reproduce the associated vibratory stimuli which are probably necessary technically in most studies, such as in studying the effects on persons asleep in a room.

8. The simulated boom generated by a device which consists of a chamber in which the air pressure can be varied by the motion of a piston driver in a prescribed way is more suitable for studies on the effects of booms on sleeping persons than the replayed recording technique.

This is a good summary of sonic boom simulation techniques. However, a more complete and extensive review was made by Edge and Hubbard (see capsule summary SM-13).

SM-15

DEVELOPMENT AND EVALUATION OF A DEVICE TO SIMULATE A SONIC BOOM

L. C. Rash, R. F. Barrett, and F. D. Hart

NASA CR-112117, May 1972

In the study described in this paper a device to simulate the vibrational and acoustic properties of a sonic boom was developed and evaluated. The design employed a moving circular diaphragm which produced pressure variations by altering the volume of an air-tight enclosure that was located adjacent to an acoustical test chamber. A review of construction oriented problems, along with their solutions, is presented in this report.

The simulator is shown to be capable of simulating sonic booms having pressure signature rise times between 5 and 30 msec, durations between 80 and 350 msec, and overpressures between 0.4 and 2.5 psf. Variations in the signature can be made by independent adjustments of the simulator. It is also shown that the energy spectral density is in agreement with theory and with actual measurements for aircraft.

This simulator is similar, in principle, to the one developed at Stanford Research Institute (see capsule summary SM-5). This type of simulation facility is the best available method of simulating indoor sonic booms, since it even simulates the structural vibration of the building due to the sonic boom.

SM-16

INITIAL CALIBRATION AND PHYSIOLOGICAL RESPONSE DATA FOR THE TRAVELLING-WAVE SONIC-BOOM SIMULATOR.

Richard Carothers

Institute for Aerospace Studies, University of Toronto, UTIAS Technical Note No. 180, August 1972

This report deals with the initial calibration of a sonic boom simulation facility which was designed

and built at the University of Toronto Institute for Aerospace Studies. Also presented are the results of tests showing the effects of sonic booms on human heart rate and hearing. However, these results are summarized in capsule summary HRSC-81.

The simulation horn was an 80 foot long pyramidal structure. The useful test section extended from a 3 foot square cross section 25 feet from the horn apex to a 10 foot square cross section at the open base. Within this test section there was room for large structural models or human and animal subjects.

Both shock-tube drivers and a mass flow valve were used to generate sonic booms and for both of these methods the main sonic-boom parameters of peak overpressure, duration, and rise time were measured. The mass flow valve is shown to be capable of producing high peak overpressures (>25 psf) and durations ranging from 70 to 500 msec, while the shock tube drivers produced short rise times of less than 0.1 msec.

It was found necessary to install inside the horn a fiberglass acoustical filtering section in order to attenuate the jet noise which was superimposed on the mass flow valve generated sonic booms. Measurements of particle velocity (induced by the simulated sonic boom) within the test section of the facility showed that the resulting dynamic pressure was negligible when compared to the peak overpressure of the sonic boom. Further measurements showed an insignificant boundary layer growth along the walls of the test section.

This simulator is similar, in principle, to the GASL/NASA simulator (see capsule summary SM-11).

SM-17
CANADIAN SONIC-BOOM SIMULATION FACILITIES
I. I. Glass, H. S. Ribner, and J. J. Gottlieb
ICAS Paper No. 72-26, Presented at the 8th Congress of the International Council of the Aeronautical Sciences, August 28-September 1, 1972

This paper describes two Canadian sonic boom simulation facilities. These were constructed at the University of Toronto Institute for Aerospace Studies in order to obtain Canadian-based data on psychoacoustic, physiological, and structural response to sonic boom. One is a loudspeaker-driven simulator which is able to mimic arbitrarily distorted sonic booms within a small booth; the other is a large horn-type simulator with a capability for generating powerful traveling-wave sonic booms of substantial spatial extent or duration. The horn and booth-type simulation facilities complement each other for the study of human, animal, and structural response to the sonic boom.

The loudspeaker-driven simulator is in the form of a solidly built booth about 70 cubic feet in volume, which can house a single seated subject. Owing to the flexibility of the electronic circuitry, features of the sonic-boom pressure signature can be adjusted at will. Thus, response to the variation of such characteristics as N-wave overpressure, rise time, and duration can be evaluated. Additionally, a variety of psychoacoustic studies can be performed with either transient or steady sounds. As a new feature, the signal can be predistorted by means of a special function generator to help cancel the loudspeaker distortion.

The traveling-wave simulator horn is in the form of a concrete horizontal pyramid 80 feet in length with a 10 by 10 feet open base. At the apex a specially-designed mass flow valve is used to generate sonic boom N-waves of suitable amplitude and duration, and acceptably short rise times; alternatively, shock-tube drivers are used for generating short-duration sonic booms. The interior of the horn contains a high frequency sound absorber to reduce undesirable jet noise, and the open end has a specially-designed reflection eliminator in the form of a recoiling porous piston.

The capacity of the loudspeakers and amplifiers of the booth-type generator were chosen to permit peak wave overpressures up to about 6 psf for short durations (100 msec) and less for longer duration waves (up to 500 msec) which are limited by slight air leakage from the booth interior. Rise times were found to be as low as 1 msec.

The mass flow valve of the traveling-wave sonic boom simulator is shown to be capable of producing high peak overpressures (>25 psf) and durations ranging from 70 to 500 msec, while the shock-tube drivers produced short duration booms with the times of less than 0.1 msec.

The traveling-wave simulation was used by Carothers (see capsule summary HRSC-81) to investigate the effects of sonic booms on human heart rate and hearing.

This is a good summary of Canadian sonic boom simulation facilities. For similar summaries of U.S. and British sonic boom simulators see capsule summaries SM-13 and SM-8, respectively.

SM-18
AN EXPERIMENTAL STUDY TO DETERMINE THE EFFECTS OF REPETITIVE SONIC BOOMS ON GLASS BREAKAGE
G. C. Kao
Federal Aviation Administration Report No. FAA-SO-70-13, June 1970

The main objective of the program discussed in this paper was to determine the cumulative damage effect on glass of repetitive sonic booms. In order to evaluate such phenomena experimentally, a pneumatic-pistonphone simulator was developed. For a description of this simulator, see capsule summary SM-64.

10.0 INSTRUMENTATION TECHNIQUES

IT-1
INSTRUMENTATION FOR MEASUREMENT OF SONIC BOOM
Harry H. Taniguchi
Noise Control, Vol. 7, March/April 1961, pp. 43-45

A discussion of the instrumentation requirements for measurement of sonic booms is presented in this paper. The essential conclusions arrived at are as follows:

1. The frequency response characteristics of the transducer used must be uniform within the range of the signal being measured.

2. The dynamic range must be adequate and the sensitivity proper to record the signal within the linear operating range of the transducer.

3. The phase shift between the input pressure and the output electrical signal of the transducer must be linear as a function of frequency.

The transducer system described in this paper to meet these requirements had a frequency response which was uniform from 2 cps to approximately 8000 cps. The input pressure and the output voltage relationship was linear within the pressure range from 0.03 to 10 lb/ft^2. Limited laboratory measurements made with the selected transducer indicated zero phase shift between the input applied pressure and the output electrical signal in the range from 2 to 20 cps. Additional measurements were in progress to cover the rest of the frequency range of interest.

The major components of the measurement system described here were the transducer system, a dc-coupled oscilloscope with attached camera to record the signal level during the test; and, to provide a permanent record of the data, a tape recorder. The output of the pressure transducer, in addition to being fed into the oscilloscope, was connected to a cathode follower. This allowed the same signal to be recorded on three different channels of the tape recorder. Setting each of the three channels at a different voltage gain insured that a proper recording of the signal would be obtained on at least one channel.

This was one of the earliest discussions of sonic boom instrumentation systems. The conclusion that a microphone with a uniform frequency response over the range from 2 cps to 8000 cps would adequately reproduce a sonic boom waveform was later outdated by the finding that a frequency range of 0.1 cps to 10,000 cps provides a much more accurate reproduction of the pressure signature (see capsule summary IT-3).

IT-2
IN-FLIGHT SHOCK-WAVE PRESSURE MEASUREMENTS ABOVE AND BELOW A BOMBER AIRPLANE AT MACH NUMBERS FROM 1.42 TO 1.69
Domenic J. Maglieri, Virgil S. Ritchie, and John F. Bryant, Jr.
NASA TN D-1968, October 1963

This paper presents the results of in-flight shock wave pressure measurements above and below a B-58. The measurements were made by an F-106 fighter with an instrumented nose boom through the shock system of the bomber. The present capsule summary discusses only the instrumented nose boom used here. For a discussion of the results of the pressure measurements, the reader is referred to capsule summary G-20.

The description of the instrumented nose boom used in this experiment is presented in the appendices of this report. The nose-boom probe was designed, fabricated, and calibrated by NASA personnel. The instrumentation was designed so as to be suitable for flight environments. It was also designed to have a high sensitivity and a frequency response that was flat from zero to 30 cps. A differential pressure gage was used to obtain high sensitivity. The required frequency response was obtained by locating the two inductance type miniature pressure gages very close to the pressure-sensing orifices. Gage 1 had a sensitivity of approximately 10 lb/ft^2 per inch of film deflection and was recorded by a 100-cycle galvanometer. Gage 2 had a sensitivity of about 20 lb/ft^2 per inch of film deflection and was recorded by a 50-cycle galvanometer. The accuracy of the overall system was estimated to be 3 percent of the peak positive overpressure.

The design and aerodynamic calibration of the nose-boom pressure probe is discussed in detail in Appendix B of this report. Briefly, the probe was of conical shape and employed six pressure-sensing systems including the two systems for indicating disturbance-related pressure changes, two systems for providing reference pressures for the differential-pressure gages, and systems for providing approximate free-stream static (ambient) pressure and pitot pressure for the airplane flight instruments. The orifices and the tube for providing approximate ambient and pitot pressures for the flight instruments were located at the bottom of the probe for all flights. The forward end of the probe was made rotatable in order to facilitate the required orientation with disturbance-sensing orifices facing the incident disturbance waves from the generating airplane. The rear portion of the probe was secured to the nose boom in such a manner that the angle of attack of the probe would be near 0° for the expected flight conditions. The miniature pressure gages in the probe were installed with their diaphragms perpendicular to the longitudinal axis of the probe in order to minimize possible effects of lateral accelerations.

An instrumented nose boom was also used in the investigation described by Smith (see capsule summary G-12).

This is a very good discussion of the special problems involved in making in-flight measurements of sonic booms.

IT-3
MEASURING THE SONIC BOOM
Jim Kyle
Electronics World, October 1964, pp. 58-60 and p. 68

This paper describes the instrumentation used during the Oklahoma City sonic boom tests of 1964 (see capsule summary SR-12, for example). The three main quantities measured during these experiments were air pressure, structural movement of specially instrumented test houses, and the speed of structural response of the test houses.

It is shown that in order to accurately reproduce the rise time and the pressure fall rate between the leading and trailing shocks, it is necessary to have a microphone with a frequency response range of 0.1 cps to 10,000 cps. Such a response range was obtained by modifying an existing microphone having a 1-10,000 cps range. The modification consisted of venting the enclosed air behind the diaphragm through specially designed vents. The complete pressure measuring unit consisted of the modified microphone, its associated electronic unit, a current amplifier, and an oscillograph.

The amount of structural movement was determined by using semiconductor strain gages, which were located at key points of the building, such as rafters and joists. Movements as small as one microinch were detectable with these gages.

Accelerometers were used to measure the motion of the structure. They were used in pairs, one pair measuring east-west acceleration and the other the north-south components. The accelerometers used in this particular experiment were of the servo type in which a feedback signal was developed and amplified to maintain the reference mass vertically stationary with respect to the accelerometer case. This "error signal" constituted the accelerometer output.

The Oklahoma City sonic boom tests were some of the most extensive ever conducted. The results of these tests are widely referred to, even to the present day. In order for later investigators to be able to determine the accuracy of the measurements made, it is important to know the type and quality of the instruments used. This paper provides that information in a clear, concise manner.

In an earlier paper (see capsule summary IT-1) it was concluded that a microphone having a uniform frequency response from 2 cps to 8000 cps would adequately reproduce a sonic boom waveform. The present paper shows that such a range is not good enough and that a range of 0.1 cps to 10,000 cps is required.

IT-4

TEST SUPPORT TO FAA SONIC BOOM TEST NEW MEXICO
M. Adams and R. McMullin
Boeing Company, Document D6-17485, March 1965

This report presents details of the instrumentation systems used to measure overpressure levels in the sonic boom tests conducted at White Sands Missile Range, New Mexico, in 1965 (see capsule summary SR-15). Six pressure measuring systems plus a direct read-out oscillograph were installed by Boeing at the test site.

The basic test instrumentation system consisted of six pressure transducers, six signal conditioning networks and one direct-write multichannel oscillograph. All components, except the transducers, were unmodified commercial equipment. The condenser microphones were modified to respond to approximately 0.5 cps by critically controlling "back-venting" across the microphone diaphragm.

The electrical response of the measurement system was essentially uniform from DC to 2500 cps. The upper frequency limitation was determined by the recording galvanometer. The low frequency response below 20 cps was determined by the back venting of the microphone diaphragm. The acoustic calibration of the microphone from 10 cps to 5 kc was done in a pressure coupler using a certified reference microphone. The back venting on each microphone was then adjusted to obtain the best compromise between good low frequency response below 10 cps and fast recovery time from static pressure variations. The back venting adjustment was done in a low frequency pistonphone which was referenced to the reference microphone at 10 cps.

The instrumentation system described here was very similar to the equipment used to measure sonic boom overpressure in the Oklahoma City tests (see capsule summary IT-3).

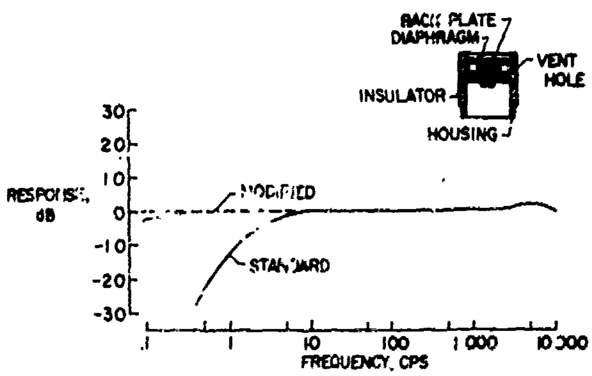
IT-5

INSTRUMENTATION TECHNIQUES FOR MEASUREMENT OF SONIC-BOOM SIGNATURES
David A. Hilton and James W. Newman, Jr.
Proceedings of the Sonic Boom Symposium, The Journal of the Acoustical Society of America, Vol. 39, No. 5 (Part 2), 19--, pp. S31-S35

This paper discusses the type of instrumentation required to measure sonic booms. A NASA instrument system is described together with measurement techniques.

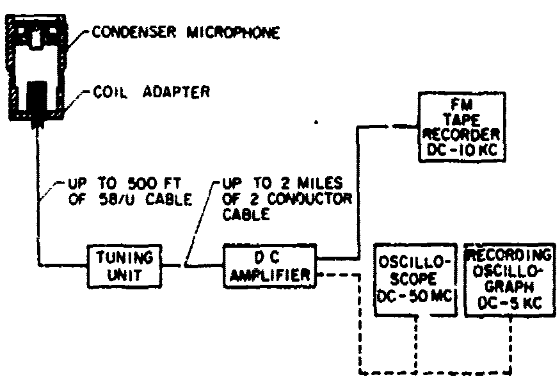
The first section of the paper treats frequency response requirements. It is shown that a system with poor low frequency response characteristics will not give an accurate reproduction of the slowly-varying portion of the wave. A system with good low frequency response but poor high frequency response will not accurately reproduce the small details associated with the rapidly rising portion of the wave and particularly the peak pressure. Thus in order to accurately reproduce all portions of the wave form the measuring system must have a usable frequency response range from nearly dc to several thousand cycles per second in the pressure range 0.1 to 10 psf.

The discussion then deals with the manner in which commercially available condenser microphones were modified to obtain the desired low frequency response characteristics. The modification consisted of changing the configuration of the chamber vent behind the diaphragm. The intermediate dashed curve shown in the figure below, which was taken from this paper, was obtained by diminishing the venting rate. It is pointed out that eliminating the vent would result in essentially dc response. However, the purpose of using the modified-vent configuration was to allow adequate provision for temperature and atmospheric pressure changes during field operations.



Frequency responses of a standard and a modified microphone

The complete measuring system in which the modified microphone was used is shown in the block diagram below, which was taken from this paper. The condensor microphone and the coil adapter unit were used together to form a tuned circuit. The use of proper signal-conditioning equipment enabled various means of data recording. Special features of the system included self-contained battery operation, the capability of driving long cables, a provision for system sensitivity checks in the field by means of static pressure devices, and the ability to produce quick-look records with the use of data-write equipment.



Block diagram of measuring system

The final portion of the discussion deals with the use of the system to obtain ground-surface measurements. In order to provide nearly perfect reflection in the area of the transducer, a reflecting board was used. This board was a rigid piece of plywood having an area about 100 times the microphone size. The microphone was installed so that its diaphragm was parallel with the reflecting board. It was shock mounted in order to minimize ground vibration effects, and a wind screen was used to isolate the microphone from the effects of wind. The wind screen consisted of a light wire frame covered with cheese cloth.

This is an excellent summary of the state of the art of sonic boom instrumentation techniques as of 1965.

IT-6
WIND-TUNNEL SONIC-BOOM TESTING TECHNIQUES
H. W. Carlson and O. A. Morris
AIAA Paper No. 66-765, Presented at AIAA Aerodynamic Testing Conference, Los Angeles, California, September 21-23, 1966

This paper describes the problems involved in wind tunnel sonic boom testing and the techniques used to overcome these problems. The most significant problems were:

1. Model and probe vibration.

2. Boundary layer effects.

3. Nonuniform and nonsteady test conditions.

4. Requirement for extreme sensitivity in measurement system.

5. Accurate construction of extremely small models.

The vibration of the probe and model combined with the boundary layer effects resulted in a measured signature which lacked sharply-defined peaks. This was overcome by adjusting the positive lobe of the measured signature to correspond to an N-wave having the same positive impulse.

Nonuniform and nonsteady test conditions resulted in pressure variations as much as several percent of the free stream static pressure. Since this may be several times greater than the maximum pressure produced by the model, these variations had to be eliminated or greatly reduced. The nonuniform and nonsteady test conditions were due to three main causes: (1) variation in free stream static pressure as the control system cycled from underpressure to overpressure; (2) variations due to small tunnel wall deformities; and (3) changes in the temperature environment of the pressure gage and the tubing external to the tunnel.

It was found that errors due to variation in free stream static pressure due to control system cycling could be virtually eliminated by locating the reference and measuring orifices of the differential pressure gage relatively close to each other and carefully balancing the time lag in the tubing. Position-dependent pressure variations due to tunnel-wall deformities were minimized by moving the model instead of the pressure orifices to get complete pressure signature and by spacing the orifices at a distance no more than that necessary to get the complete pressure signature.

Changes in the temperature environment of the gage and tubing external to the tunnel resulted in less severe, more gradual deviations of differential gage pressure with time. It was found that this effect could be virtually eliminated by the locking of doors during the run or the application of insulation.

It was found that the necessary sensitivity of measurement could be achieved only by using a differential pressure gage with a maximum range not too much greater than the model-created pressures.

The models used ranged in size from 1/4" to 4". In order to achieve accurate scaling the construction methods employed specialized machine tools which allowed the use of oversize master models. A number of operations were performed under binocular microscopes and alignment jigs were used to a considerable extent.

This paper is a good summary of the state of the art of sonic boom wind tunnel testing techniques as of 1966. A later paper by Morris and Miller (see capsule summary IT-13) presents a similar discussion but for higher Mach numbers.

IT-7
A FEASIBILITY INVESTIGATION CONCERNING THE SIMULATION OF SONIC BOOM BY BALLISTIC MODELS
J. G. Callaghan
NASA CR-603, October 1966

This report presents the results of a series of tests to determine the feasibility of using ballistic models to provide laboratory simulation of sonic boom. The test program consisted of two main parts: (1) the determination of appropriate instrumentation to measure the pressure signature of small-scale rapidly moving ballistic models, and (2) the definition of problems associated with launching winged ballistic models. Only the first part of the program will be summarized here. For a discussion of the second part, see capsule summary SM-3.

In order to ensure the best possible reproduction of the pressure signature associated with the particular model in question, two approaches were used. The testing of commercially available pressure transducers was conducted, as well as the testing of transducers especially tailored to the particular requirement of the subject study.

It was found that commercially available transducers could provide, in a rapid fashion, good quality pressure signatures resulting from shock wave systems of ballistic models in flight. Measured maximum overpressures were generally higher than theoretically predicted levels. It was felt that this was due primarily to nonlinearity in transducer sensitivity.

Specially tailored transducers showed promise of improvement in the quality of pressure signatures over those commercially available. The tailoring techniques consisted mainly of modifying the diaphragm to change resonance and damping characteristics.

The discussion presented in this paper is not very relevant to the measurement of actual sonic boom pressure signatures due to the fact that the frequency range of interest is much higher in this case. However, it does illustrate the special problems involved in instrumenting for ballistic simulation of sonic booms.

IT-8
CALIBRATION OF PHOTOCON PRESSURE TRANSDUCER
R. Brown and J. J. Van Houten
NASA-CR-66369, March 1967

This is a very short report describing the application of the techniques discussed in capsule summary IT-9 to the calibration of three Photocon microphone systems. The calibration included a measurement of the frequency response of the transducers obtained by use of an infrasonic pistonphone in the range from 0.01 to 10 Hz. The effect on transducer sensitivity of changes in transducer balance sensitivity was evaluated and found to vary considerably with balance meter reading. An electrostatic actuator was used to obtain both the steady state response of the transducer as well as the rise time and overshoot characteristic to a step function. Finally, utilizing the electrostatic actuator system, the Photocon transducer response to an ideal N-wave was obtained.

IT-9
INVESTIGATION OF THE CALIBRATION OF MICROPHONES FOR SONIC BOOM MEASUREMENT
J. J. Van Houten and R. Brown
NASA CR-1075, 1968

The purpose of the investigation described in this paper was to provide NASA with the tools necessary for the precise calibration of microphones to be used for sonic boom measurement. The calibration requirements included the ability to evaluate the sensitivity of the transducer, its linearity over the range of pressures of interest, and its frequency response over a broad range from infrasonic pressures extending through the audio frequency range. Also of interest in examining the capability of the transducer for a given transient measurement situation were its rise time and overshoot characteristics. It was found that all of these requirements could be satisfied by the use of two devices: an electrostatic actuator and an infrasonic pistonphone.

The electrostatic actuator was used to determine the steady-state frequency response characteristics of the microphone at low audio frequencies to well above 20 KHz and sound pressures approaching 1 lb/ft^2. It also provided a method of subjecting the microphone to both idealized N-wave and step function pressures for evaluation of rise time, overshoot, and flat top response characteristics. The electrostatic actuator applies an electrostatic pressure to the microphone diaphragm by setting up an electric field between the parallel plates consisting of the microphone diaphragm and the actuator. The effective sound pressure on the diaphragm is then calculated using Gauss' Law. The upper limit of achievable pressure was found to be about 1 psf due to the fact that the stronger electric fields necessary to induce higher pressures resulted in voltage breakdown caused by arcing across the plates.

The infrasonic pistonphone was used to establish microphone sensitivity, linearity, and low frequency response characteristics in the frequency range from 0.01 to 10 Hz. The pistonphone generates an altering pressure above the ambient in a closed chamber by the sinusoidal motion of the piston. Since the dimensions of the chamber and the displacement and diameter of the piston are known, the pressure level can be calculated very accurately.

This is an excellent discussion of microphone calibration techniques.

IT-10
EFFECT OF GROUND REFLECTIVE AND OTHER MICROPHONE MOUNTING CONDITIONS ON SONIC BOOM MEASUREMENTS
Manlio Abele, Roger Tomboulian, William Peschke, and Daniel Dantuono
Federal Aviation Administration, Report No. FAA-NO-70-4, May 1970

This report presents the results of an investigation into the effects of various ground surfaces on the characteristics of a reflected N-wave. The effect of microphone height and wave incidence angle with respect to both a rigid surface and several ground surfaces was evaluated in the GASL sonic boom simulator (see capsule summary SM-11). The ground surfaces tested included asphalt, coarse aggregate, medium density grass, spaded soil and several others. Also included in the investigation was an evaluation of the electrical-acoustical free field characteristics of FAA-supplied microphones as referenced to a standard

microphone over the range of frequencies from .01 to 10,000 Hz.

The following conclusions were reached concerning the effects of microphone height, wave incidence angle, and ground surface on the characteristics of the reflected wave.

1. The main effect of varying the microphone height above the ground surface was an alteration of the time interval between the arrival of an incident wave at the microphone location and the reflection of the wave from the ground surface.

2. Placement of the microphone outside the zone of influence defined by an angle equal to twice the wave incidence angle resulted in data exhibiting some distortion of the wavefront.

3. Varying the incident wave angle resulted in only minor changes in reflected wave amplitude for the configuration tested.

4. The results of the ground surface tests indicated a 5-1 spread in reflectivity of the samples tested. The ratio of reflected-to-incident wave amplitude for each of the materials tested was as follows: dry, spaded soil - .22; sod on sod - .22; plywood on sod - .555; sparse grass - .22; gravel - .445; asphalt on gravel - .445, and fiberglass blanket on asphalt - .11.

This was a significant investigation in that it was the first to deal specifically with the effects of microphone height, wave incidence angle, and ground surface characteristics on the measured waveform.

IT-11
SONIC-BOOM WIND-TUNNEL TESTING TECHNIQUES AT HIGH MACH NUMBERS
Odell A. Morris and David S. Miller
AIAA Paper No. 71-280, Presented at AIAA 6th Aerodynamic Testing Conference, Albuquerque, New Mexico, March 10-12, 1971

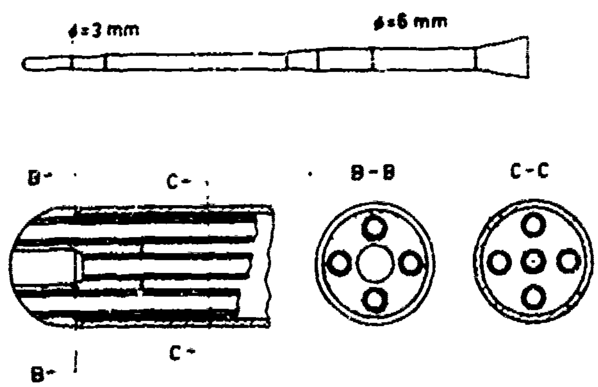
This paper is exactly the same as the one covered in capsule summary IT-13. The reader is referred to that capsule summary for details of this work.

IT-12
A NEW METHOD FOR DETERMINING SONIC BOOM STRENGTH FROM NEAR-FIELD MEASUREMENTS
M. Landahl, I. Rhyming, H. Sorensen, and G. Drougge
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 285-295

This paper presents a method of determining the F-function of a body based on accurate wind-tunnel measurements of the flow inclination angles along a cylindrical surface surrounding the wind tunnel model. Using equations developed in another paper (see capsule summary G-61) the measured downwash angles and azimuthal deflection angles can be used to determine the velocity perturbations and velocity potential to second order. Knowing these quantities, the F-function can then be calculated.

The theory will not be treated in depth here, since this capsule summary deals specifically with the instrumentation techniques used in this procedure. For a discussion of the theory, (see capsule summaries G-61 and G-62).

The flow inclination angles were determined using the hemispherical differential pressure yaw meter shown in the figure below, which was taken from this paper. The pressure probe had a diameter of 3.5 mm. Four static pressure orifices were located circumferentially 90° apart on the hemispherical surface, and four on the cylindrical surface. A pitot-pressure orifice was located at the probe apex. The static pressure orifice diameters were 0.5 mm and the pitot-pressure orifice diameter was 1.0 mm.



Pressure yaw meter

The model was mounted on a sting and could be moved back and forth (400 mm), making possible a complete survey of the flow field along a line parallel to the flow direction. The pressure probe was mounted fixed on the top wall.

The free stream properties were considered accurate within the following limits: ± 0.01 for M_∞ and ± 0.1 percent for $P_{t,\infty}$ (total pressure). The precision with which local flow quantities (for $M_\infty = 3.0$) could be determined was estimated to be ± 0.07 for M_1, ± 1.0 percent for $P_{t,1}$ and $\pm 0.10°$ for the downwash angle ϵ, where M_1 is the local Mach number (ahead of shock wave at probe apex) and $P_{t,1}$ is the local total pressure.

This method was a significant advancement over previous wind tunnel techniques, in that it allowed a second order determination of the F-function, in contrast to previous methods which made no corrections for the nonlinear effects occurring in the near-field of the model.

IT-13
SONIC BOOM WIND-TUNNEL TESTING AT HIGH MACH NUMBERS
Odell A. Morris and David S. Miller
Journal of Aircraft, Vol 9, No. 9, September 1972, pp. 664-667

This paper discusses some of the problems encountered and testing techniques employed in measuring sonic boom overpressures in the Mach number range between 2.3 and 4.63. It was found that the problems encountered in testing at the lower supersonic Mach numbers, such as the presence of tunnel flow nonuniformities, probe and model vibration, and the boundary layer on the measuring probe were enhanced at the higher Mach numbers. However, employing the same techniques used at the lower supersonic Mach numbers (see capsule summary IT-6) solved those problems.

The most significant new problem encountered was concerned with interference from the model mounting strut and the angle of attack mechanism. The equipment which provided interference-free measurements of sonic boom signatures in the lower Mach number range produced interference pressures at high Mach numbers that tended to blanket out a large portion of the model signature. This problem was overcome by using an offset strut to separate the model signature from the pressure field produced by the angle of attack mechanism. The strut cross-sectional area in the region of the sting-strut mount was reduced as much as possible to prevent a strong strut-produced shock wave from merging with the pressure field generated by the model.

A subject mentioned in the earlier paper by Carlson and Morris (see capsule summary IT-6), the use of a miniature one-component strain-gage balance for measuring model lift, is covered in much more depth in the present paper.

This is a good summary of the state of the art of sonic boom wind tunnel testing techniques as of 1972.

IT-14
REPORT ON THE SONIC BOOM PHENOMENON, THE RANGES OF SONIC BOOM VALUES LIKELY TO BE PRODUCED BY PLANNED SST'S, AND THE EFFECTS OF SONIC BOOMS ON HUMANS, PROPERTY, ANIMALS, AND TERRAIN.
Attachment A of ICAO Document 8894, SBP/II, Report of the Second Meeting of the Sonic Boom Panel, Montreal, October 12 to 21, 1970.

This report is composed of six chapters, each dealing with a certain aspect of sonic boom phenomena. The present capsule summary summarizes only Appendix B of Chapter 1, entitled "Measurement of Physical Properties of Sonic Boom." The method detailed provides for the measurement and description of sonic boom signatures.

The following are some of the requirements given for the equipment used in the measuring system:

1. The measuring chain shall have an overall free-field frequency response over the range of at least from 0.1 Hz to 5000 Hz, which shall be flat within $\pm$ 2 dB. Extension of the frequency range to 0.01 Hz and/or to 10,000 Hz is advisable depending on the signature duration and the need for information about the acoustic energy over this total bandwidth.

2. The sensitivity of the microphone system above the frequency range of interest shall have a smooth roll-off in order to restrict overshoot distortion in the recording of soni booms with short rise time.

3. For most applications a dimension not exceeding 20 mm is recommended for the sensitive surface of the microphone.

4. The variations of the sensitivity of the microphone due to environmental conditions shall be corrected in such a way that the resulting sensitivity is within $\pm$ 0.3 dB of the calibration value.

5. The dynamic range of the recorder shall be at least 45 dB, under the condition that the total harmonic distortion is less than 1% measured at 1000 Hz.

6. For recording sonic booms over a long period specially designed data recorders should be used since conventional recording systems are limited in operation for this purpose. The recorder should include the capability for unattended operation and instantaneous response to transients.

7. For initial evaluation of the sonic boom pressure signature the signal may be displayed on an oscilloscope. For detailed analysis other display devices such as digital read-out or a precision galvanometer may be necessary depending on the accuracy required.

8. The result of a frequency analysis shall be given in the form of either a spectral density function or frequency band spectrum.

9. The following datum ground conditions are given: (a) conditions of an open space that is essentially free from local undulations, and obstructions that in total subtend a solid angle of more than 0.004 steradians; (b) there shall be a hard surface surrounding the measurement point, in the form of a securely fixed rigid plane baffle in intimate contact with the ground. The baffle should be preferably not less than 1.5 m in diameter.

10. Datum free field conditions are obtained when the obstructions in the upper half-space subtend a solid angle of less than 0.004 steradians and when the microphone can be mounted at a sufficient height.

11. The microphone shall be mounted with its axis perpendicular to the ground with its sensitive surface facing upwards and flush with a hard surface at ground level. All voids and cavities between the microphone and the baffle shall be filled with a suitable sound absorbing material.

12. Freedom from extraneous signals shall be obtained. A shield may be necessary in order to reduce the effects of wind on the microphone or to protect it from rain and dirt. Such a shield shall be designed so that the response of the microphone is not significantly affected. The microphone shall be adequately shock-mounted to reduce vibrations transmitted through the mountings.

The specifications given in this report for the equipment characteristics required to adequately measure sonic booms are the most extensive, complete, and up-to-date available.

11.0 UNSUCCESSFUL CONCEPTS

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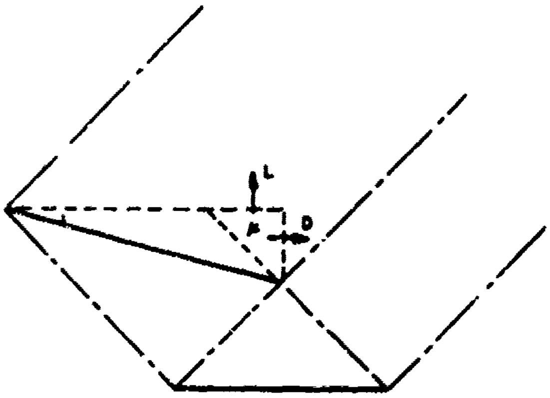
UC-1
A BOOMLESS WING CONFIGURATION
E. L. Resler, Jr.
NASA SP-147, Sonic Boom Research, 1967, pp. 109-113

In this paper an aerodynamic configuration designed to achieve lift with no boom by affecting only air above the wing is discussed. The figure below, which was taken from this paper, shows the airfoil configuration. The configuration was designed to reflect all waves upward.



Airfoil configuration

Using a first-order theory, it is shown that the configuration gives a second order lift. However, the configuration does not result in lift using any higher order theory. The reason is shown to be due to the asymmetry of the curve for pressure p versus Prandtl - Meyer function, ν, combined with the asymmetry of the configuration - a compression followed by a compression and a single expansion.

Even though the scheme presented here is not successful, the approach and discussion are instructive, which was the author's purpose in presenting it.

In a later paper (see capsule summary M-34) Resler proposed "processing" the air between the plates in order to obtain lift.

UC-2
ELECTROAERODYNAMICS IN SUPERSONIC FLOW
M. S. Cahn and G. M. Andrew
AIAA Paper No. 68-24, Presented at AIAA 6th Aerospace Sciences Meeting, New York, New York, January 22-24, 1968

This paper presents the results of an investigation into the possibility of reducing sonic boom strength by the use of electrostatic fields. The basic idea consisted of applying a very high electrostatic potential to the forward portion of a supersonic airplane. Oncoming air of the same charge as this potential would be repelled and thereby warned of the presence of the obstacle. The path of the air molecules around the airplane could thus be changed more smoothly, thereby making the discontinuity at the shock weaker.

Several experiments were carried out to study the effects of electrostatic fields on a charged flow of fluid about a body. The first was a hydraulic analogy test in which a charged rod was inserted into a flowing liquid. It was found that, starting at about 2,000 volts and roughly proportional to the voltage, a continuous spreading of the shock pattern resulted.

In the second experiment a charged body of revolution was tested in a five-inch supersonic wind tunnel at a Mach number of about 2.75. Some tests indicated a very slight increase in the shock thickness. However, due to the leakage of current from the nose of the model to the tunnel walls, it was not possible to create an isolated body of charged air around the model nose, and no conclusive results were obtained.

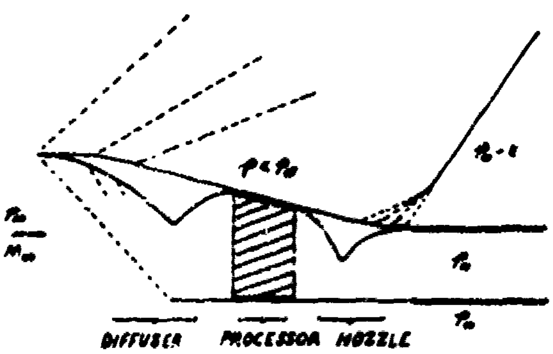
The final experiment discussed also used the hydraulic analogy. In this experiment a two dimensional ellipse charged with 30,000 volts was immersed in a flow of transformer oil. It was found that when the ellipse was charged, the bow shock became several shocks of lesser intensity and spread over a larger region than when the ellipse was not charged.

An extensive analysis of the feasibility of the concept proposed here was made in a later paper by Cheng and Goldburg (see capsule summary UC-4). They found that, using this scheme, a 10% reduction of the boom intensity of an SST would require on the order of thousands of megawatts of electric power. Millions of pounds of electrical equipment would be required to generate this electricity. More importantly, however, they found that the scheme proposed here is unsound in concept as well, in that, instead of the presumed weak aerodynamic interaction, a strong interaction would actually take place. This would result in a blunt-body effect and a detached bow wave, which, in turn, would result in increased drag and increased boom intensity.

UC-3
AERODYNAMIC CONFIGURATIONS YIELDING LIFT WITHOUT SONIC BOOM
Robert W. Porter
Journal of Aircraft, Vol. 5, No. 6, Dec. 1968.

This short note deals with the reduction of the sonic boom due to lift. The technique suggested here is to design a wing which develops lift by low pressure on its upper surface but does not disturb the flow over its lower surface. Discussion is restricted to two-dimensional, frictionless flow.

The figure below illustrates the type of wing which is proposed. The pressure on the upper surface of the wing is lower than the freestream pressure p_∞, while the pressure on the lower surface is equal to the freestream pressure. The internal flow is processed in such a way that it exhausts at the freestream pressure and through an exit with area less than the inlet area. The matching of pressure prevents interaction with the freestream. Whether or not thrust is produced depends on the internal process.



Schematic of ideal, lifting, boom-free configuration

in order to evaluate the performance of such a device, a special case is considered where there is zero exit area, all internal flow being absorbed. It is shown that, because of the reliance on suction alone, the lift at a small angle of attack would be about half that of a flat plate. It is found that the lift-drag ratio is about one order of magnitude smaller, at angle θ of optimal lift of the present device, than for the flat plate at the same angle of attack. This is due to the absorption of mass and the reaction to its momentum. It is pointed out that the absorption of such large flow rates obviously makes the configuration impractical with known technology. In the more general device, where the exit area is not zero, alteration of energy could be substituted for the mass sink of the present example. The amount of drag would then depend on the internal process.

It is concluded that, although it does not seem entirely possible to eliminate the sonic boom because of wake and end effects, the contribution due to lift can be eliminated.

Resler proposed a similar concept (see capsule summary M-61) at about the same time the present scheme was proposed.

UC-4

AN ANALYSIS OF THE POSSIBILITY OF REDUCTION OF SONIC BOOM BY ELECTRO-AERODYNAMIC DEVICES

Sin-I Cheng and Arnold Goldburg

AIAA Paper No. 69-38, Presneted at AIAA 7th Aerospace Sciences Meeting, New York, New York, January 20-22, 1969

This paper presents a theoretical evaluation of the feasibility of reducing sonic boom by electro-aerodynamic schemes (see capsule summary UC-2). A one dimensional model is used to analyze the interaction of ions and electrons of an electric discharge with neutral particles in moving air. A simple expression is given for the change of total stream thrust ($p+\rho u^2$, less the electric pressure $E^2/8\pi$) due to the electric wind mechanism, and a calculation of the power required to maintain the discharge is made. It is found that the specific power requirement of the proposed electroaerodynamic devices for deflecting the oncoming air of the supersonic transport is of the order of 1/2 megawatt/pound force.

It is concluded that a 10% reduction of the boom intensity of a supersonic transport would require on the order of thousands of megawatts of electric power. At the present technology level for power equipment of 4 to 5 pounds per kilowatt, electrical equipment on the order of millions of pounds would be required.

In addition to the prohibitive power requirements, it was also found that the electro-aerodynamic schemes are unsound in concept as well, in that the presumption of weak aerodynamic interaction cannot be achieved due to the requirement of spatial continuity of fluid properties at the centerline in the absence of solid boundaries. Under the actual strong interaction, a detached bow wave results, which results in both increased drag and increased boom.

Miller and Carlson also made a feasibility study of the use of force-fields to reduce sonic boom (see capsule summary UC-8). Their analysis was not as rigorous as that of the present paper. However, they arrived at essentially the same conclusions.

UC-5

AN ANALYSIS OF DEVICES FOR REDUCING SONIC BOOM

Sin I. Cheng and Arnold Goldburg

AGARD Conference Proceedings No. 42, Aircraft Engine Noise and Sonic Boom, May 1969, pp. 6-1 thru 6-11

This paper is essentially the same as the one described in capsule summary UC-4. The reader is referred to that capsule summary for details.

UC-6

REDUCTION OF SHOCK WAVE STRENGTH BY MEANS OF NON-UNIFORM FLOW

Scott Rethorst, Morton Alperin, William Behrens, and Toshio Fujita

Air Force Flight Dynamics Laboratory, Technical Report AFFDL-TR-69-62, Part I, July 1969

This report presents the results of a preliminary study conducted to investigate the feasibility of utilizing nonuniform flow mechanisms to (1) improve supersonic aircraft performance by essentially eliminating dissipative shock losses, and (2) alleviate the sonic boom associated with shock wave propagation. The effort was directed toward defining a wind tunnel model configuration employing a simple nonuniform flow generated by integrating the propulsive and lifting elements to reduce shock waves emanating from the system.

The arrangement was comprised of a propulsive unit located ahead of the lifting surface so that the jet issued adjacent to the concave underside of the lifting surface.

The central idea underlying this scheme was that the shocks due to lift could be eliminated by an ordered nonuniform external flow along the underside of the wing. It was hypothesized that such a flow would bring about the thermodynamic changes in the flow necessary to satisfy boundary constraints and thus eliminate the shock wave which would normally be required to bring about these changes.

A wind tunnel test plan was developed to investigate and confirm the analytical findings. The results of the test are covered in Part II of this report (see capsule summary UC-7).

The results of an independent analysis of the present study were reported by Weeks in the paper summarized in capsule summary UC-10. That analysis showed the present scheme to be "without significant merit."

UC-7

REDUCTION OF SHOCK WAVE STRENGTH BY MEANS OF NON-UNIFORM FLOW

Scott Rethorst, Morton Alperin, and Toshio Fujita

Air Force Flight Dynamics Laboratory, Technical Report AFFDL-TR-69-62, Part II, July 1969

This is Part II of a two-part report. See capsule summary UC-6 for a discussion of Part I. The Part II effort carried out the planned wind tunnel tests and developed what the authors claimed was an improved analytical method for prediction of far-field shock characteristics from the wind tunnel data. The wind tunnel tests included several simple configurations to investigate the validity of

the basic nonuniform shock attenuation mechanism. The analytical work included development of a "second order" theory for prediction of far-field shock intensities from the near field and surface pressures measured in the test.

The wind tunnel results, after being extrapolated to the far field using the theory developed in this report, showed shock attenuations on the order of 30% to distances in excess of 1000 chord lengths of the lifting surface.

An independent analysis was made of this study (see capsule summary UC-10), and the results of that analysis showed that, even under the most favorable conditions, the reduction in shock strength could not exceed 9%, in contrast to the 30% reduction found here. Furthermore, that analysis showed that the "second order" theory of the present paper was in reality a first order theory.

UC-8
A STUDY OF THE APPLICATION OF HEAT OR FORCE FIELDS TO THE SONIC-BOOM-MINIMIZATION PROBLEM
David S. Miller and Harry W. Carlson
NASA TN D-5582, December 1969

A study of the feasibility of proposed sonic boom minimization schemes involving the use of heat or force fields (see capsule summary UC-2, for example) is presented in this paper. In this study, attainment of a finite rise-time signature is considered to be the objective. The analysis is centered upon the "phantom-body" shape which would be defined by the altered flow field streamlines resulting from the heat or force fields. The study is concerned with the considerations dictating the required phantom-body shape, the variation in flow properties within the phantom-body, and the distribution and magnitude of the power required to divert the flow and create the phantom-body. One-dimensional channel flow equations are used in the solution for the phantom-body characteristics, and no consideration is given to the ultimate source of the heat or force field or the size, weight, and efficiency of the generating equipment.

The following conclusions were reached as a result of this investigation:

1. The treatment of an illustrative example for a proposed supersonic transport configuration at a cruise Mach number of 2.7 indicated that, subject to the simplifying assumptions made in the study, finite rise-time signatures are theoretically obtainable but require the creation of a carefully controlled heat or force field extending several airplane lengths ahead of and behind the airplane itself. A complicating factor is the not insignificant variation of the flow properties within the phantom body which alters the airplane aerodynamic performance.

2. Under the simplifying assumptions of this study, and for idealized conditions with weightless power generation equipment and no energy dissipation, a power expenditure roughly equivalent to twice that necessary to sustain the airplane in steady level flight would be necessary to create the heat or force field ahead of the airplane.

3. It was also discovered that not only must some means be found to deliver continuously large quantities of power to the air in the proper manner, but means must also be provided to extract power from the air in a prescribed manner.

Cheng and Goldburg (see capsule summary UC-4) also made a feasibility study of electro-aerodynamic devices. Although their analysis was more rigorous than that of the present investigation, they arrived at essentially the same conclusions.

Batdorf (see capsule summary UC-11) proposed a heat addition scheme in which external burning of fuel would be used. He found that, theoretically, the rise time of the front shock could be increased to 10 msec by external burning of fuel at a rate equal to 20% of the fuel consumption rate of the aircraft.

UC-9
SONIC BOOM MINIMIZATION SCHEMES
David Siegelman
Journal of Aircraft, Vol. 7, No. 3, June 1970, pp. 280-281.

The purpose of this short note is to present simple analytical techniques with which proposals involving mass or energy addition or electro-aerodynamic schemes may be evaluated and to obtain some preliminary results concerning their feasibility. The objective of the proposed schemes (see capsule summaries UC-2, UC-8, and UC-11) is to create a "phantom" boundary which will favorably alter the effective area distribution of a given airplane. The effective area variation required of the addition scheme is, therefore, the difference in effective areas between the phantom and actual bodies. Assuming that this distribution has been selected, the problem becomes one of relating the required area growth to a causal mass or energy distribution. Identifying the phantom boundary as the "dividing streamline" for cases involving mass injection only, the mass distribution required to produce a given variation in area under the flight conditions of interest are determined by application of the results of slender body theory.

The analysis of energy addition schemes is more complex. It is stated that the model adopted should be dependent upon the proposed manner in which the energy is to be added (conduction, convection, radiation). The problem is viewed as essentially an inviscid interaction problem in which the flow within a reference streamtube tries to expand in area (due to heat addition) against a self-induced retarding pressure gradient.

Using these analytical models, the mass or energy requirements to suitably modify the effective area distribution of a simple cone-cylinder-subsonic leading edge delta wing configuration is estimated. It is found that the mass flow rate is about the total capability of the SST engines. For a heat addition scheme, it is found that a power level of 1/3 million horsepower is required, which is approximately 70% of the engine capability. It is concluded that the mass and energy addition schemes are probably not competitive with configurational changes as sonic boom minimization techniques.

Similar but more extensive analyses of this topic were made by Miller and Carlson (see capsule summary UC-8) and by Miller (see capsule summary UC-12).

UC-10

CRITICAL EVALUATION OF A NONUNIFORM FLOW SONIC BOOM REDUCTION CONCEPT

Dr. Thomas M. Weeks

Air Force Flight Dynamics Laboratory, Technical Report

AFFDL-TR-70-65, September 1970

This report presents the results of an independent analysis of a study performed by Rethorst, et al (see capsule summaries UC-6 and UC-7) involving sonic boom reduction by means of nonuniform flow and to check the approach and pertinent results contained in their final report.

It is shown from a fundamental standpoint that the Rethorst concept of introducing a nonuniform flow field ahead of a flat plate to eliminate the sonic boom is without significant merit. The delivery of a uniform jet flow to the undersurface of an inclined flat plate without regard to the practical internal and external aerodynamic consequences of the delivery system cannot be construed as an attack on the sonic boom problem, in the opinion of the author of the present paper. What has been analyzed is a two-dimensional flow interaction problem with attention focused primarily on the strength of the emerging shock wave.

The analysis of this problem by Rethorst, et al, was, in their view, second order. In the present report it is shown that, on the contrary, their analysis was formally first order (linear). Furthermore, when properly modified to include the correct expression for downstream Mach number, their numerical results for the reference plate coincided with those obtained in the present paper.

From the results of the present investigation or from the corrected Rethorst results, it is concluded that at 1000 chord lengths from the trailing edge the percent relative attenuation of the shock from the jet-plate model compared to that from the reference model for the same chord and lower surface pressure under the most favorable conditions cannot exceed 9% whereas the former claimed a reduction of 30%.

UC-11

ON ALLEVIATION OF THE SONIC BOOM BY THERMAL MEANS

S. B. Batdorf

AIAA Paper No. 70-1323, Presented at AIAA 7th Annual Meeting and Technical Display, Houston, Texas, October 19-22, 1970

This paper presents an analysis of the possibility of achieving a finite-rise-time sonic boom by heating the air in the vicinity of the aircraft. The purpose of the heat is to simulate a long body, since an aircraft length of at least 850 feet would be required to produce a finite-rise-time signature. The heat expands the stream tube surrounding the body, effectively modifying the area distribution of the body. Through proper addition of the heat it is proposed that the aircraft effective length can be increased and its effective area distribution can be modified to correspond to a 5/2 power body, thus resulting in a finite-rise-time pressure signature.

Two methods of adding this heat to the flow are investigated--a "thermal-spike" and a "thermal-keel." The "thermal-spike" concept is based upon the addition of heat in the region ahead of the airplane by such means as the radiant energy from a laser or the external burning of jet fuel. The "thermal-keel" concept is based upon the fact that, within the framework of linear theory, a point on the ground experiences a pressure disturbance that is independent of the location of the source along the Mach line. Thus, instead of generating heat in a distributed and properly tailored fashion along the horizontal axis, the heat is distributed along a vertical axis below the airplane in the proper fashion. It is concluded that the heat consumption would be the same in both cases if, in the process of creating the heat, there were no losses and no net drag or thrust.

A calculation of the required power showed that it would be about 60% of the SST cruise power. However, it was found that the required heat could also be obtained by the external burning of fuel at a rate amounting to a little less than 20% of the cruise rate of fuel consumption of the SST.

Miller and Carlson (see capsule summary UC-8) also investigated the use of heat fields to obtain a finite rise time sonic boom. They concluded that a power expenditure roughly equivalent to twice that necessary to sustain the airplane in steady, level flight would be required. However, as pointed out by the author of the present paper, when the differing approaches taken in each of the two investigations is taken into account, no sizable discrepancies remain in the results of the two investigations.

It is also pointed out in the present paper that the results of Cheng and Goldburg (see capsule summary UC-4), which were widely interpreted as invalidating any nonmechanical approach, including the use of heat, for the avoidance of the shock, only apply under conditions giving rise to strong interaction, and not under the weak interaction conditions proposed here.

The scheme proposed in the present paper has several weaknesses:

1. No method is given for controlling the thermal area precisely enough to produce the $X^{5/2}$ area variation necessary to eliminate the front shock.

2. A 20% increase in fuel consumption would only increase the rise time of the front shock--the rear shock would be unaffected. To produce a finite rise time front and rear shock would require approximately a 50% increase in fuel consumption.

3. The entire study is done for effects under the airplane. No check is made of the effects produced to the side of the flight path on the ground.

UC-12

STATUS OF RESEARCH ON BOOM MINIMIZATION THROUGH AIRSTREAM ALTERATION

David S. Miller

NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 325-340

A study is presented in this paper of the potential benefits to be gained, the problems encountered, and the power required in the application of heat-field concepts to the sonic boom minimization problem. The theoretical method employed to analyze the altered airstream flow properties and to estimate the heat distribution and power requirements is based on the assumption that the flow within the airstream can be treated as the steady, one-dimensional, inviscid channel flow of a perfect gas. The solution is found by defining the channel area development, establishing boundary conditions, and applying influence coefficients and iterating.

The assumptions included in this analysis are that the radial and azimuthal variations are ignored, that the heat transfer from the airstream is not considered, that the interaction of the airstream and the airplane is neglected, and that the shocks at the airplane surface are assumed to be weak.

The purpose of the heat-field is to create a "phantom body" whose area development completely envelopes the airplane area development and produces a finite rise time signature. The required total area development has a 5/2-power variation with length to prevent bow shock formation. Prevention of a tail shock is accomplished by a design process for the remainder of the phantom-body area development, which involves trial-and-error application of a computing program solution of the Whitham equations (see capsule summary G-3).

To assess the problems to be encountered in practical application of the concept, an illustrative example for a representative SST configuration at cruise speed was treated. In order to create the proper airstream alterations, it was found that power amounting to more than the airplane's propulsion power output must be supplied to the forepart of the airstream and by some unknown means extracted from the aft part. Significant variations in the airstream flow properties and large gradients in the heat distribution were also encountered.

It was found that the thermal-fin implementation of the phantom-body concept proposed by Batdorf (see capsule summary UC-11) could be extended to prevent formation of both the bow and tail shock without the necessity of heat extraction; however, airplane reshaping as well as thermal fin heat addition is required. For a typical SST at cruise speed, it is estimated that, with direct burning, the bow and tail shock elimination could be accomplished with 60 percent additional fuel.

Siegelman (see capsule summary UC-9) also presented an analysis of energy or mass addition schemes. His conclusion was that such schemes are probably not competitive with configurational changes as sonic boom minimization techniques.

UC-13
AN ANALYTICAL STUDY OF SOME POSSIBLE SONIC BOOM ALLEVIATION SCHEMES
R. W. Lipfert
AIAA Paper No. 72-653, Presented at AIAA 5th Fluid and Plasma Dynamics Conference, Boston, Mass., June 26-28, 1972

The objective of the present study was to consider all identifiable means of altering the flow near the aircraft that could improve the ground signature, to examine the technical feasibility and practicality of achieving the desired flow field modifications, and to include a realistic assessment of the aircraft penalties incurred in the implementation of these various schemes. Finite rise times, reduced overpressures, and reduced shock pressure rises were among the signature improvements investigated. Flow field alteration mechanisms considered included free combustion, boundary layer mass addition, force-fields, and laser-generated heat fields. In evaluating these various schemes, linearized theory is used to relate force, heat, and mass injection terms to an effective area distribution.

The following conclusions were reached as a result of this study:

a. Use of air stream alteration schemes to modify a complete sonic boom signature (i.e., complete shock elimination, substantial shock pressure rise reduction, etc.) will require gross weight penalties on the order of 100% of the baseline aircraft weight and thus is not considered practical.

b. A precursor signal warning of the arrival of the sonic boom may be generated through airstream alteration at substantially less gross weight penalty, and thus may be a practical scheme. The benefit to be derived from such a warning must be established through psychoacoustic studies of startle phenomena.

c. The weight penalty (to the baseline aircraft) for boom alleviation may be substantially reduced through the concept of a separate penalty aircraft, the lift distribution of which is used to form part of the boom alleviation effective area. This concept may be extended to include payload-carrying penalty aircraft or two SST's flying "in formation" in such a way as to create favorable signature interference.

This paper is very similar to an earlier paper by Siegelman (see capsule summary UC-9). Both reach the same conclusions regarding the various exotic sonic boom minimization schemes. However, the present paper treats a much larger number of examples and deals with the subject in more depth than the earlier paper.

12.0 SONIC BOOMS OF AIRCRAFT

SBA-1
GROUND MEASUREMENTS OF THE SHOCK-WAVE NOISE FROM AIRPLANES IN LEVEL FLIGHT AT MACH NUMBERS TO 1.4 AND AT ALTITUDES TO 45,000 FEET
Domenic J. Maglieri, Harvey H. Hubbard, and Donald L. Lansing
NASA TN D-48, September 1959

This report is concerned mainly with sonic boom propagation, and for a summary of these results the reader is referred to capsule summary P-20. The present capsule summary is concerned only with the sonic boom characterisitcs of the test airplanes used in this investigation.

The table below, which was taken from this report, shows the measured overpressures and signature lengths at various altitudes and lateral distances for test airplane 1, which was an F-101, and at one altitude and lateral location for test airplane 2, which was an F-100. The dashed lines signify that no sonic boom was observed on the ground for that particular case. The signatures from both airplanes were simple N-waves.

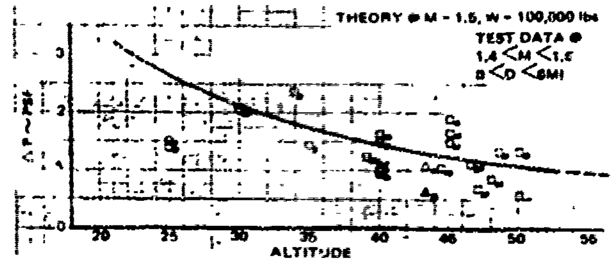
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Measured ground shock peak overpressures

A comparison of a measured and calculated pressure signature for an F-101 is given in capsule summary SBA-13.

SBA-2
SONIC BOOM THEORY AND THE B-58
E. L. Crosthwait
Convair Report No. FZA-4-405, April 28, 1961

In this report Walkden's theory (see capsule summary S-6) is used to make a detailed analytical evaluation of the bow shock overpressure along the flight track for a B-58A airplane in steady flight. The results are then compared with measured overpressures. The figure below which was taken from this paper shows the comparison between theory and measured results for M = 1.5 which is the case for which the most data was available. Although the data scatter is as much as 50% on each side of the theoretical prediction, the mean of all test points is near the predicted level. The overpressure can be seen to vary from about 2 psf at 30,000 feet to about 1 psf at 50,000 feet.



B-58 overpressures

Another illustration of the variation of overpressure with altitude for the B-58 is given in capsule summary SBA-8. For a sample of actual measured pressure signatures of the B-58, see capsule summary SBA-6.

SBA-3
MICROBAROGRAPH MEASUREMENTS AND INTERPRETATIONS OF B-58 SONIC BOOMS, PROJECT BIG BOOM
Jack W. Reed
Sandia Corporation Research Report No. SC-4634(RR), December, 1961

In the investigation discussed in this paper pressure signatures were recorded at ground level from seventeen supersonic flights of B-58 bombers at Indian Springs, Nevada, using microbarograph equipment. The measurements shows that the overpressure varied from about 1.5 psf for flight at 30,000 feet and M = 1.5 to about 0.5 psf at 50,000 feet, also for M = 1.5. However, the measured pressure signatures were of very poor quality due to a lack of adequate high frequency response in the instrumentation.

For a good illustration of the variation of overpressure with altitude for the B-58, see capsule summary SBA-8. For a good example of measured pressure signatures of the B-58, see capsule summary SBA-6.

SBA-4
A PRELIMINARY DATA REPORT ON GROUND PRESSURE DISTURBANCES PRODUCED BY THE FAIRY DELTA 2 IN LEVEL SUPERSONIC FLIGHT
T. A. Holbeche
Aeronautical Research Council R & M No. 3296, 1963

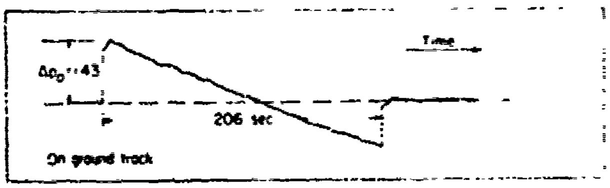
This report presents the results of a series of measurements of the sonic booms produced by a Fairy Delta 2 in straight level flight in the altitude range from 3,500 feet to 30,000 feet at Mach numbers up to about 1.5. The measured pressure signatures varied in shape, but were generally of the N-wave type. Overpressures varied from 0.3 to 4.0 psf, the large range being due to the fact that for most of the measurements the airplane was either accelerating or decelerating.

The quality of these measurements was somewhat low due to the instrumentation available at the at the time of this study.

SBA-5
LATERAL-SPREAD SONIC-BOOM GROUND-PRESSURE MEASUREMENTS FROM AIRPLANES AT ALTITUDES TO 75,000 FEET AND AT MACH NUMBERS TO 2.0
Domenic J. Maglieri, Tony L. Parrott, David A. Hilton, and William L. Copeland
NASA TN D-2021, 1963

The investigation discussed in this paper is summarized in capsule summaries P-36 and G-19. The present capsule summary discusses only the results concerning the sonic boom characteristics of the test airplanes used in this investigation, which were an F-104, F-106, and a B-58.

The measurements show that the strength of the bow shock overpressure varies from the 3-4 psf range at an altitude of 10,300 feet to the 0.5 - 1 psf range at an altitude of 43,200 feet and a Mach number of 1.44 for the F-104. For the F-106 measurements made at an altitude of 41,000 feet and a Mach number of 2.0 showed an overpressure under the flight track of about 1.2 psf. For the B-58, the overpressure under the flight track was found to vary from about 2.4 - 3.1 psf for flight at 31,200 feet and M = 1.50 to about 1.0 psf at an altitude of 70,000 feet and a Mach number of 1.7. The figure below, which was taken from this paper, shows a typical pressure signature for a B-58 at an altitude of 61,000 feet and a Mach number of 2.0.



B-58 pressure signature

A good illustration of the variation of overpressure with altitude for the F-104 and B-58 is given in capsule summary SBA-8. Additional samples of measured pressure signatures for the B-58 are given in capsule summary SBA-6. See capsule summary SBA-12 for examples of F-104 pressure signatures.

SBA-6

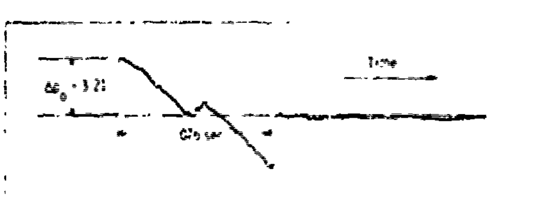
GROUND MEASUREMENTS OF SONIC-BOOM PRESSURES FOR THE ALTITUDE RANGE OF 10,000 to 75,000 FEET

Harvey H. Hubbard, Domenic J. Maglieri, Vera Huckel, and David A. Hilton

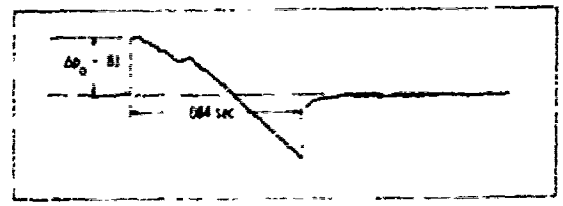
NASA TR R-198, July 1964

The investigation presented in this paper is summarized in capsule summary G-23. The present capsule summary discusses only the results concerning the sonic boom characteristics of the two test aircraft - a B-58 and an F-104.

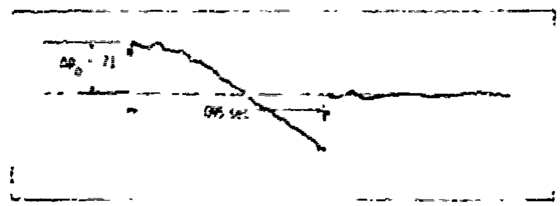
The first figure below, which was taken from this paper, shows the sonic boom pressure signatures resulting from steady, level flight of the F-104 at various altitudes and Mach numbers. The signature can be seen to change from the near-field-type, having an intermediate shock wave, for flight at 10,300 feet and M = 1.24 to a far-field N-wave for flight at 51,000 feet and M = 1.93.



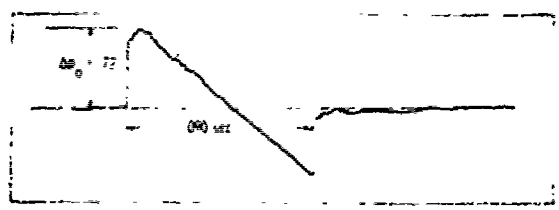
altitude, 10,300 feet; M = 1.24.



altitude, 32,200 feet; M = 1.34.



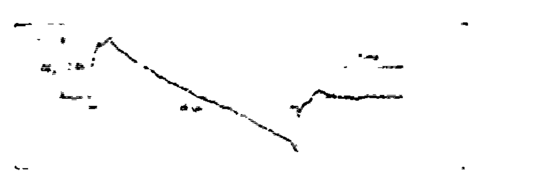
altitude, 43,200 feet; M = 1.44.



altitude, 51,000 feet; M = 1.93.

F-104 pressure signatures

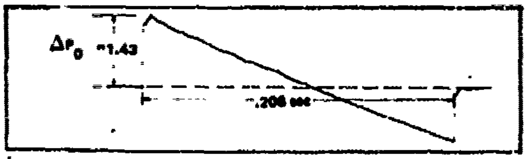
Sonic boom pressure signatures for the B-58 at various altitudes and Mach numbers are shown in the figure below, which was also taken from this paper.



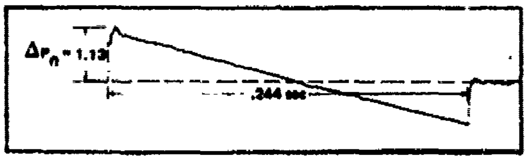
Altitude, 31,200 feet; M = 1.5.

Altitude, 42,... feet; M = 1.6.

Altitude, ... feet; M = 2 ...



Altitude, 61,100 feet; M = 2.0.



Altitude, 70,700 feet; M = 1.72.

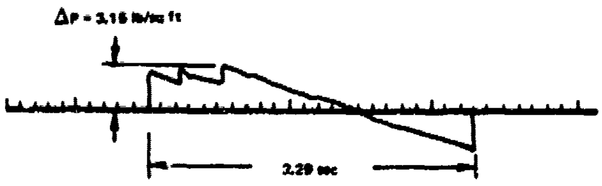
B-58 pressure signatures

See capsule summary SBA-8 for an illustration of the variation of overpressure with altitude for the F-104 and the B-58.

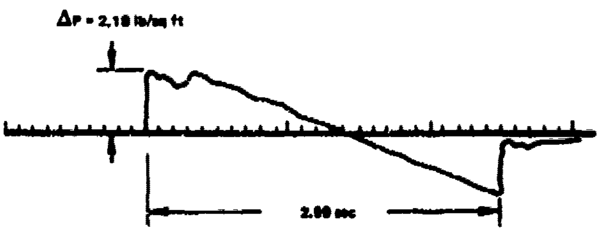
SBA-7
SUMMARY OF PRELIMINARY DATA FROM THE XB-70 AIRPLANES
William H. Andrews
NASA TMX-1240, June 1966

This report presents preliminary data on the XB-70 in the areas of stability and control, general performance, propulsion-system inlet operation, structural thermal response, internal noise, runway noise, and sonic boom. Only the sonic boom characteristics of the XB-70 will be summarized here.

The figure below, which was taken from this paper, shows typical measured pressure signatures for the XB-70. The signature measured for flight at M = 1.22 at an altitude of 27,000 feet is of the near-field type, while that measured for flight at M = 1.86 at an altitude of 48,000 feet is of the N-wave type.



M = 1.22, Δh = 27,000 ft, gross weight = 423,000 lb.

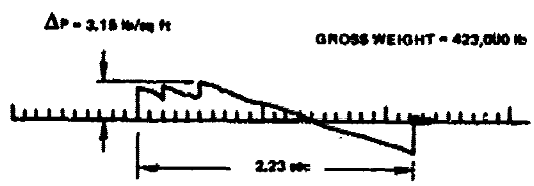


M = 1.4, Δh = 38,700 ft, gross weight = 387,000 lb.

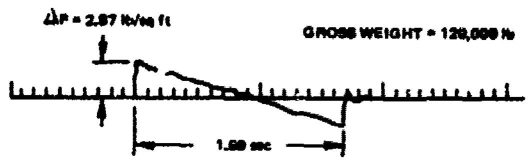
M = 1.86, Δh = 48,000 ft, gross weight = 362,000 lb.

XB-70 pressure signatures

A comparison of XB-70 and B-58 pressure signatures for flight at M = 1.22 and an altitude of 27,000 feet is shown in the figure below, which was also taken from this paper. It can be seen that, while the XB-70 pressure signature is of the near-field type, the B-58 pressure signature has already attained the far-field N-wave form.



XB-70 airplane.



B-58 airplane.

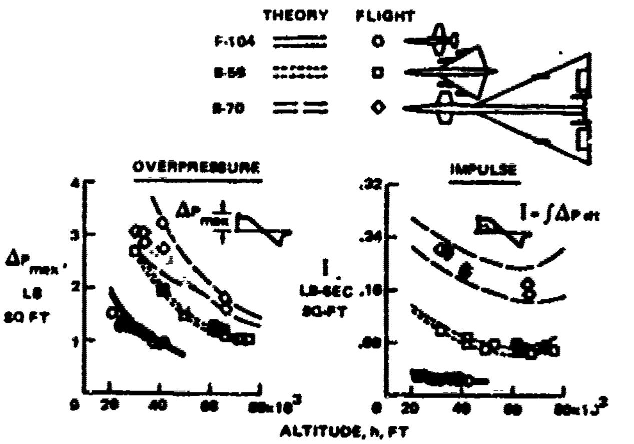
Comparison of XB-70 and B-58 pressure signatures

See capsule summary SBA-8 for an illustration of the variation of overpressure with altitude for the XB-70, and capsule summary SBA-9 for an illustration of the variation in signature shape with increasing distance from the XB-70.

SBA-8
SONIC-BOOM CHARACTERISTICS OF PROPOSED SUPERSONIC AND HYPERSONIC AIRPLANES
F. Edward McLean and Harry W. Carlson
NASA TN D-3587, September 1966

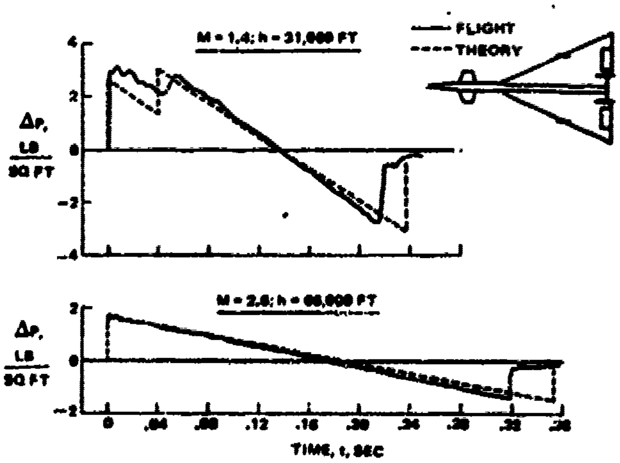
This paper relates the predicted sonic boom characteristics of the large, heavy supersonic and hypersonic airplanes to those of the supersonic airplanes that were operational at the time. It also explores the use of near-field effects to modify the sonic booms of the proposed airplanes. For a summary of this discussion the reader is referred to capsule summary M-14. The present capsule summary deals only with the sonic boom characteristics of the F-104, B-58, and B-70, as discussed in this paper.

The figure below, which was taken from this paper, shows correlations of the measured and theoretical sonic boom characteristics of the F-104, the B-58, and the B-70. For both overpressure and impulse the theoretical predictions are represented as a band of values to account for differences in operating weight and Mach number at a given altitude. It can be seen that there are substantial increases in overpressure and impulse with increased airplane size.



F-104, B-58, and B-70 sonic boom characteristics

A comparison of measured and theoretical ground pressure signatures for the B-70 are shown in the figure below, which was also taken from this paper. The upper signature shows near-field characteristics. The major disagreement between theory and flight measurements is in the tail-shock portion of the signature where the wake conditions and engine exhaust plumes are difficult to define.



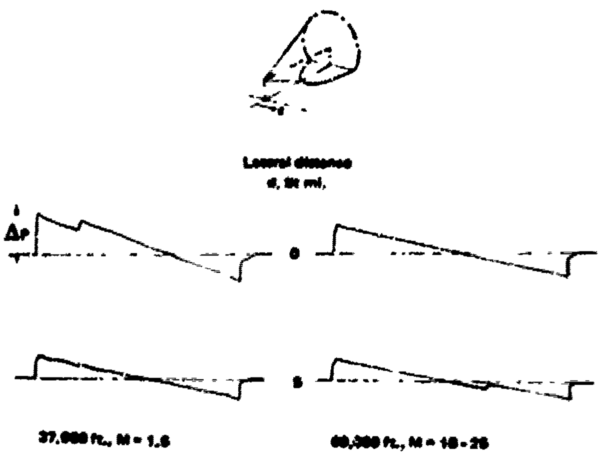
B-70 pressure signatures

See capsule summary SBA-6 for samples of measured pressure signatures of the B-58 and the F-104. Measured pressure signatures for the B-70 are shown in capsule summaries SBA-7 and SBA-9.

SBA-9
PRELIMINARY RESULTS OF XB-70 SONIC BOOM FIELD TESTS DURING NATIONAL SONIC BOOM EVALUATION PROGRAM
D. J. Maglieri, V. Huckel, H. R. Henderson, and T. Putman
Sonic Boom Experiments at Edwards Air Force Base, Interim Report, NSBEO-1-67, Annex C, Part II, July 28, 1967

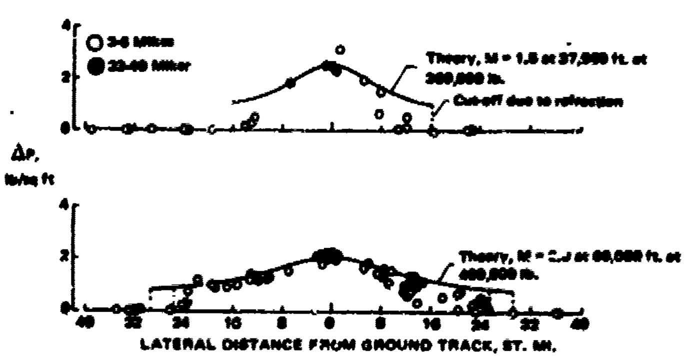
This report documents the measurements made from XB-70 sonic boom flight tests conducted as part of the Edwards Air Force Base sonic boom experiments. The present capsule summary is concerned only with describing the sonic boom characteristics of the XB-70, as demonstrated by the results of this investigation. For a discussion of the other results found in this investigation see capsule summary P-163.

The figure below, which was taken from this report, shows tracings of typical sonic boom signatures measured at two different lateral stations and for two different flight conditions of the airplane. It can be seen that the signature measured on the ground track for a flight altitude of 37,000 feet and a Mach number of 1.5 is of the near-field type. At a lateral distance of 5 miles the signature was of the far-field type for a flight altitude of 37,000 feet and Mach number of 1.5, but it was of the near-field type for a flight altitude of 60,000 feet and a Mach number of 1.8 - 2.5. The reason for the existence of the additional relatively weak shock wave was not fully understood, but it was thought to be due to the variable geometry features of the airplane.



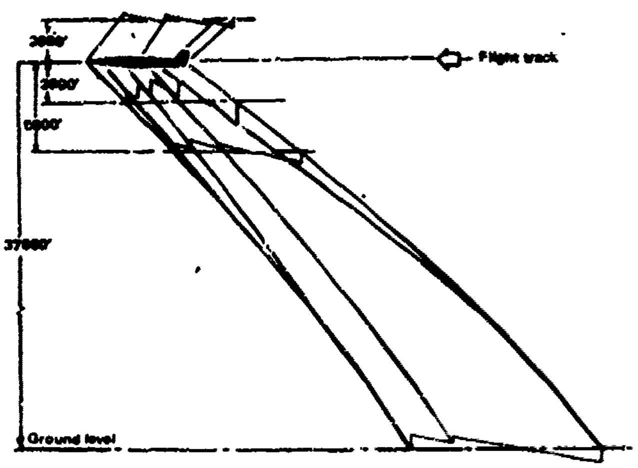
XB-70 pressure signatures for two different flight conditions

The variation of overpressure with lateral distance for the XB-70 for flight at two different altitudes is shown in the figure below, which also was taken from this paper. It can be seen that for stations not on the flight track the measured overpressure values were generally lower than the calculated values.



XB-70 pressure signatures as a function of lateral distance

The final figure shows sample in-flight wave forms measured at various distances from the XB-70 using an instrumented F-104. It can be seen that more complex signatures were measured close to the aircraft and that the individual shock waves tended to coalesce as distance from the aircraft increased. It can also be seen that the pressure signature above the airplane differed markedly from that below the airplane at a comparable distance. This is due to the fact that there are suction forces on the upper surface of the wing and compression forces on the lower surface.

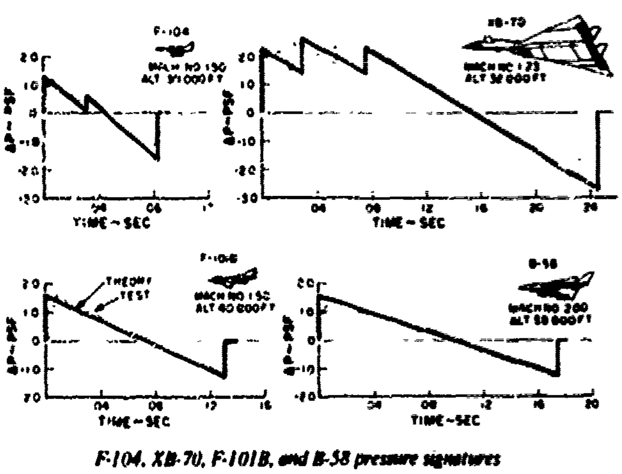


Near-field XB-70 waveforms

This report contains one of the most extensive descriptions available concerning the sonic boom characteristics of the XB-70.

SBA-10
SOME EFFECTS OF THE ATMOSPHERE ON SONIC BOOM
Edward J. Kane
NASA SP-147, Sonic Boom Research, 1967, pp. 49-63

This paper is primarily concerned with atmospheric effects on sonic boom propagation. The reader is referred to capsule summary P-74 for a summary of these effects. The present capsule summary is concerned only with the figure below, which was taken from this paper and which shows measured and theoretical pressure signatures for an F-104, an XB-70, an F-101B, and a B-58. It can be seen that the resemblance between the measured and calculated pressure signatures is very close.



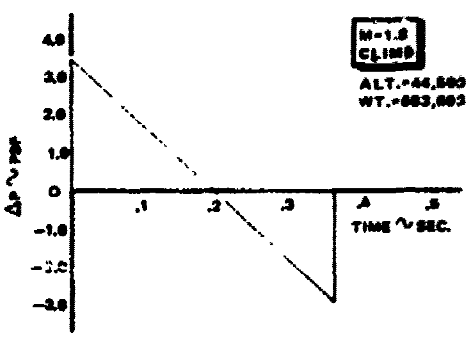
F-104, XB-70, F-101B, and B-58 pressure signatures

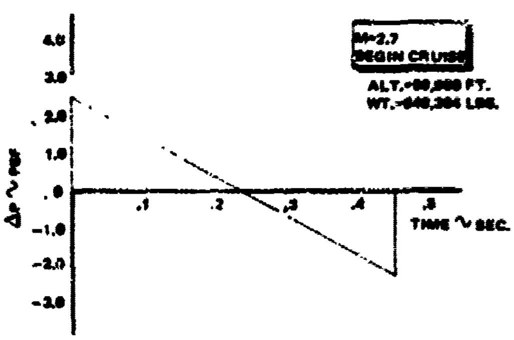
Measured sonic boom characteristics of the F-101 are also presented in the paper summarized in capsule summary SBA-1. However, no pressure signatures are shown in that paper. Additional examples of measured F-104 pressure signatures are given in capsule summary SBA-12. Capsule summaries SBA-7 and SBA-9 give additional samples of XB-70 measured pressure signatures, and capsule summary SBA-6 gives additional B-58 signatures.

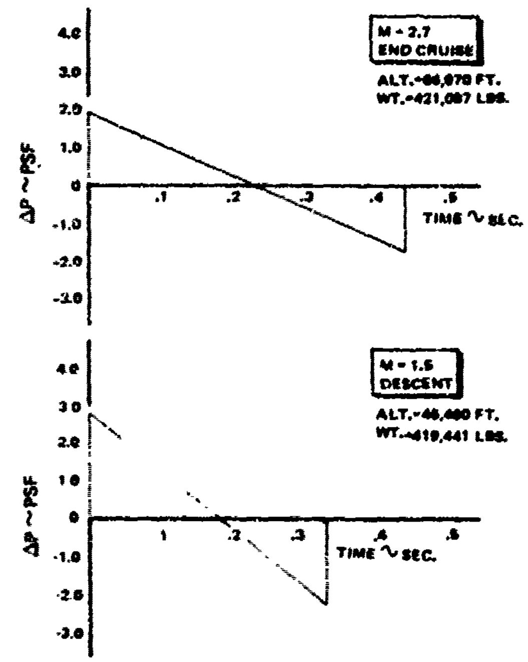
SBA-11
MODEL 2707-300 SONIC BOOM DOCUMENT
Edward J. Kane and W. L. Paulin
Boeing Company, Commercial Airplane Division, Document No. D6 A11541-1 TN, January 1969.

This document contains calculated pressure signatures of the 2707-300 airplane during supersonic climb, cruise, and descent. These signatures were calculated using Whitham's theory (see capsule summary G-3) in conjunction with the use of an atmospheric correction factor to account for the effects of a non-homogeneous atmosphere. The atmospheric correction factor was calculated using a method equivalent to that of Hayes, et al (see capsule summary P-98).

The four signatures below show the sonic boom characteristics of the 2707-300 during climb, beginning cruise, end cruise, and descent. All signatures are for a maximum taxi weight (MTW) of 750,000 pounds. It can be seen that the signature is of the far-field N-wave type for all four cases. The maximum overpressure varies from about 3.5 psf during climb to about 2.0 psf at the end of cruise.







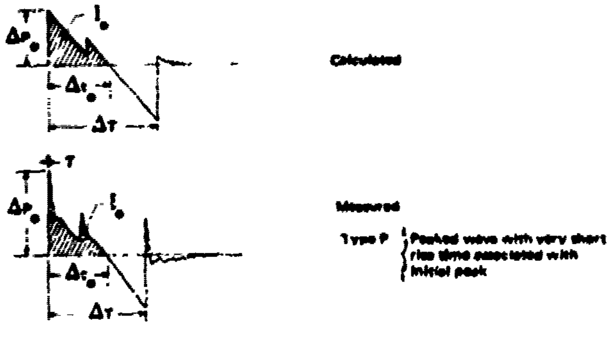
2707-300 Pressure signatures

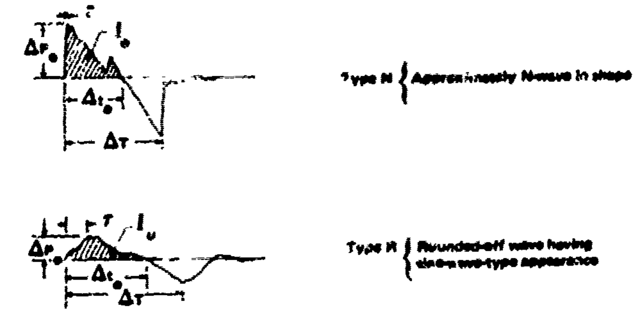
Further characteristics of the calculated 2707-300 sonic boom, together with a comparison of Concorde sonic boom characteristics are given in capsule summary SBA-13. For a summary of the sonic boom characteristics of the Russian-built TU-144 see capsule summary SBA-19.

SBA-12
VARIABILITY IN SONIC-BOOM SIGNATURES MEASURED ALONG AN 8000-FOOT LINEAR ARRAY
Domenic J. Maglieri, Vera Huckel, and Herbert R. Henderson
NASA TN D-5040, February 1969

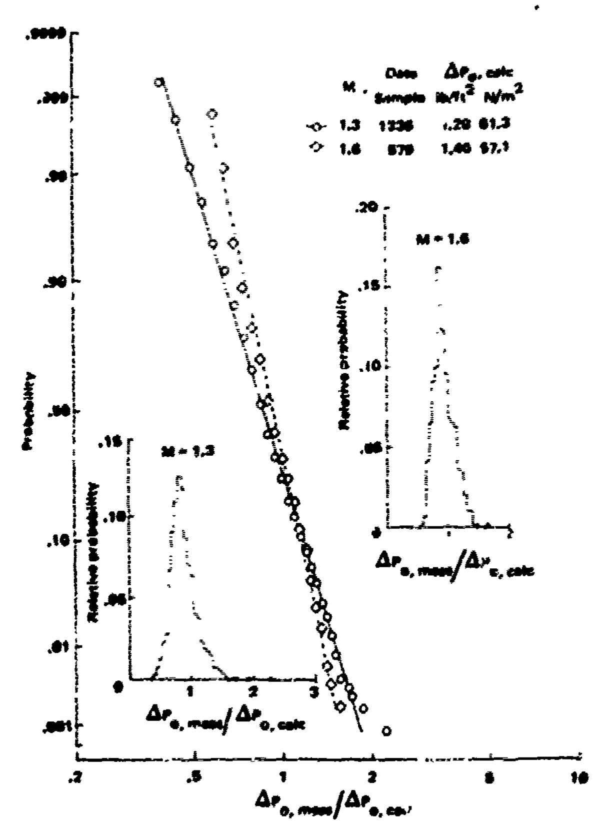
For a summary of the investigation presented in this paper the reader is referred to capsule summary P-94. The present capsule summary discusses only the results concerning the sonic boom characteristics of the F-104.

The first figure below, which was taken from this paper, shows calculated and measured pressure signatures for the F-104 at a flight altitude of 30,000 feet and a Mach number of 1.3. The second figure, which also was taken from this paper, shows a histogram of measured overpressures, as influenced by atmospheric variability, for the F-104 for flight at an altitude of 30,000 feet and at Mach numbers of 1.3 and 1.6. It can be seen that nearly all of the overpressures lie in the 0.5 to 2.0 psf range and that the mean overpressure is about 1.0 psf.





F-104 pressure signatures



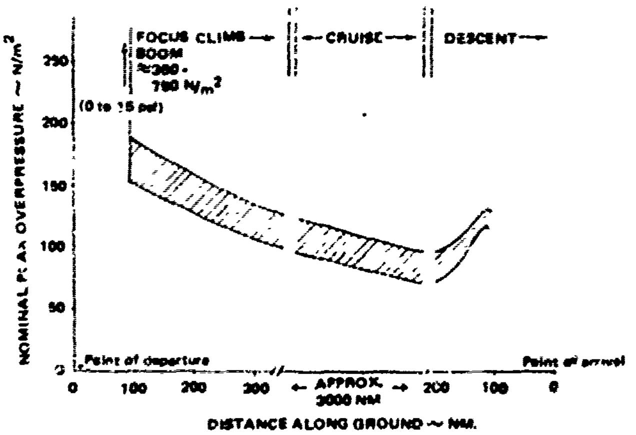
Probability of equaling or exceeding a given value of the ratio of measured to calculated overpressures

See capsule summary SBA-6 for an illustration of the variation of overpressure with altitude for the F-104. Capsule summary SBA-6 gives additional examples of measured pressure signatures for the F-104.

SBA-13
REPORT ON THE SONIC BOOM PHENOMENON, THE RANGES OF SONIC BOOM VALUES LIKELY TO BE PRODUCED BY PLANNED SST's AND THE EFFECTS OF SONIC BOOMS ON HUMANS, PROPERTY, ANIMALS, AND TERRAIN
Attachment A of ICAO Document 8894, SBP/II, Report of the Second Meeting of the Sonic Boom Panel, Montreal, October 12 to 21, 1970

This report is composed of six chapters, each dealing with a certain aspect of sonic boom phenomena. The present capsule summary summarizes only the second chapter, which is entitled "Ranges of Sonic Boom Values Likely to be Produced by Planned SST's."

In the absence of detailed data on the Tupolev 144 developed by the U.S.S.R., the data presented in this chapter of the report relate to the Concorde and the Boeing 2707. The figure below, which was taken from this report, shows the range of nominal overpressures that were expected to be produced by these two airplanes for climb, cruise, and descent. The upper line represents the 2707-300 project with a takeoff gross weight of 750,000 pounds and the lower line represents the Concorde. It can be seen that the values of the nominal peak overpressure range from about 180 N/m^2 (3.6 psf) in the beginning of climb (after the initial focus boom) to about 100 N/m^2 (2 psf) at the end of cruise.



Nominal SST peak overpressures

It is stated that the nominal signature interval will range from about 250 to 300 milliseconds for the Concorde to about 300 to 350 milliseconds for the 2707-300. The carpet width of the Concorde for a flight altitude of 56,000 feet is 45 NM, while that of the 2707-300 is given as 50 NM for a flight altitude of 63,000 feet.

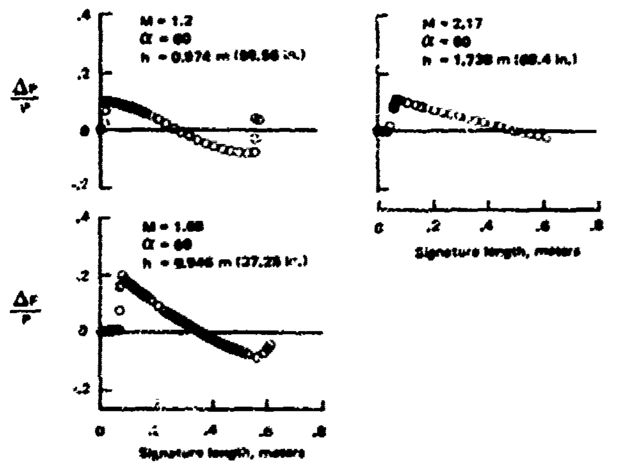
No pressure signatures for either airplane are given in this report. See capsule summaries SBA-20 and SBA-23 for measured Concorde pressure signatures and capsule summary SBA-11 for calculated 2707-300 pressure signatures. Sonic boom characteristics of the TU-144 are summarized in capsule summary SBA-19.

SBA-14
AN INVESTIGATION OF SONIC BOOM FOR STRAIGHT AND DELTA WING SPACE SHUTTLE ORBITERS
Raymond M. Hicks, Joel P. Mendoza, and Lionel L. Levy, Jr.
NASA-TM -2930, April 1971

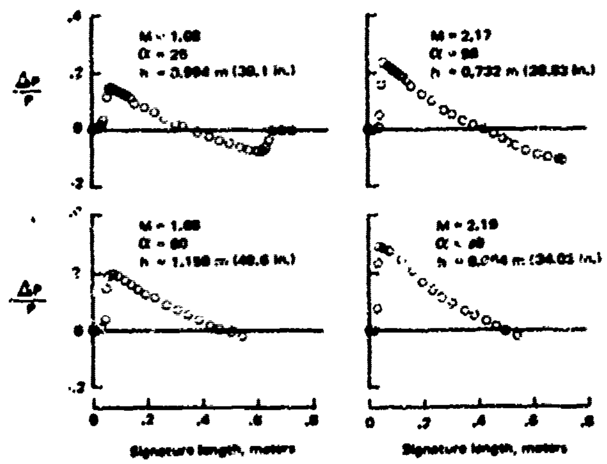
In the investigation discussed in this report wind tunnel tests were conducted to determine the sonic boom characteristics of straight-wing and delta-wing space shuttle orbiters during re-entry into the earth's atmosphere. Two different trajectories were analyzed for the delta-wing orbiter, while one trajectory was considered for the straight-wing orbiter. Both trajectory and angle of attack were found to have strong effects on the level of sonic boom overpressure under the flight path of the vehicle.

The straight-wing orbiter was tested at Mach numbers of 1.2, 1.68, 2.17, and 2.7. The delta-wing orbiter was tested at Mach numbers of 1.68, 2.17, and 2.7. The sonic boom overpressures generated by the straight-wing orbiter were found to vary from approximately 2 psf at M = 1.2 to about 0.9 psf at M = 2.7 for a trajectory based on a constant angle of attack of 60 degrees during re-entry. The level of sonic boom overpressures for the delta-wing orbiter was found to be approximately the same as that of the straight-wing orbiter for a 60 degree angle of attack trajectory. When the trajectory was changed to permit a constant angle of attack of 25 degrees during reentry, the overpressure was less than 1 psf for the range of Mach numbers investigated.

The two figures below, which were taken from this paper, show the measured pressure signatures of both models at various Mach numbers. The straight-wing orbiter model had a length of approximately 7 inches, while the delta-wing model was about 10 inches long. Thus the signatures shown are near-field signatures. The extrapolation technique developed by Hicks and Mendoza (see capsule summary SBA-34) was used to obtain the far-field overpressures.



Straight-wing orbiter



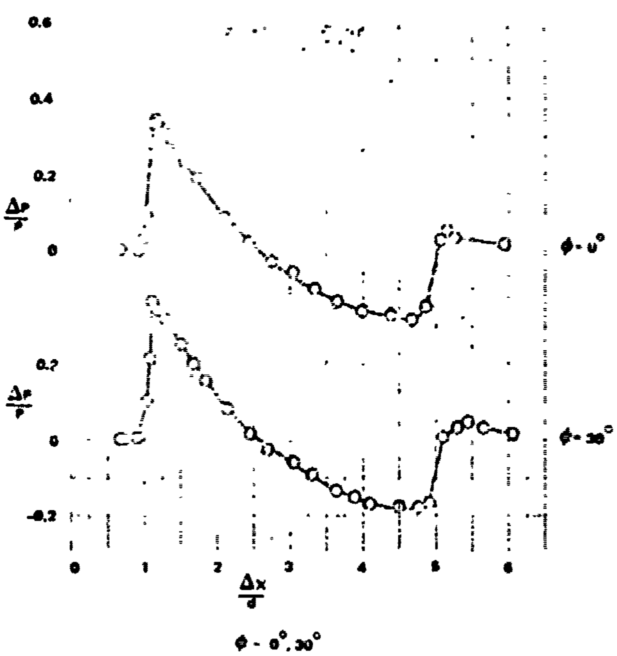
Delta-wing orbiter

The sonic boom characteristics of the space shuttle during ascent were investigated in the report summarized in capsule summary SBA-16.

SBA-15
WIND TUNNEL PRESSURE SIGNATURES FOR A .016-SCALE MODEL OF THE APOLLO COMMAND MODULE
Joel P. Mendoza and Raymond M. Hicks
NASA TMX-62,047, July 14, 1971

In the investigation discussed in this report a wind tunnel test was conducted to measure the overpressure characteristics of a .016-scale model of the Apollo command module. Pressure signatures for the model at 25° angle of attack were measured at roll angles ranging from 0° to 180°. Schlieren photographs were taken at 0° roll angle. The test Mach numbers ranged from 1.50 to 10.02.

An example of the pressure signatures measured is shown in the figure below, which was taken from this paper. The signatures are for a Mach number of 2.0, a angle of attack of 25°, a distance to body diameter ratio of 2.85, and roll angles of 0° and 30°, respectively.



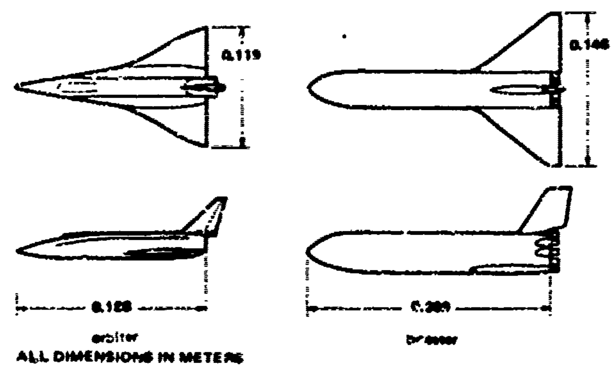
Apollo command module pressure signatures.
M = 2.0, α = 25°, h/d = 2.85

No attempt was made in this paper to extrapolate the measured near-field signatures to obtain far-field overpressures.

Actual measurements of pressure signatures of the Apollo 15 command module are presented in the paper summarized in capsule summary SBA-21. Also, a correlation of wind tunnel and flight-measured signatures is presented in the paper summarized in capsule summary SBA-18.

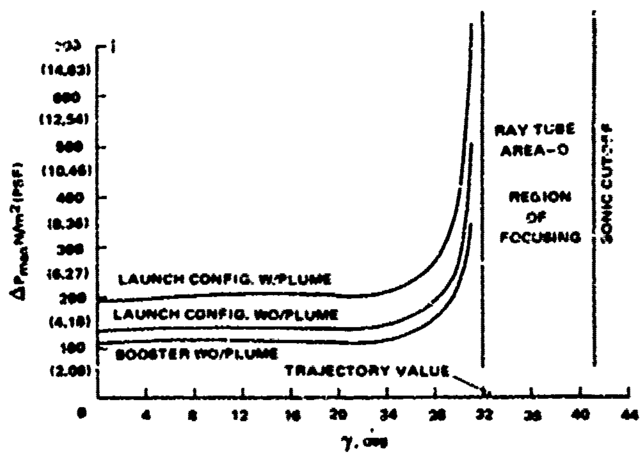
SBA-16
A BRIEF STUDY OF THE SPACE SHUTTLE SONIC BOOM DURING ASCENT
Raymond M. Hicks and Joel P. Mendoza
NASA TM X-62,055, July 23, 1971

This paper presents the results of an experimental investigation conducted to determine if a sonic boom problem existed during ascent of a space shuttle launch configuration. A model of the North American Rockwell orbiter in combination with a General Dynamics Convair booster (see sketch below) was tested with and without a simulated exhaust plume. Wind tunnel pressure signatures were obtained at Mach 3 and 4 for angles of attack and bank of zero. These signatures were used to calculate ground overpressures under the flight path for launch trajectory developed by the Manned Spacecraft Center using the extrapolation technique developed by Thomas (see capsule summary P-151.

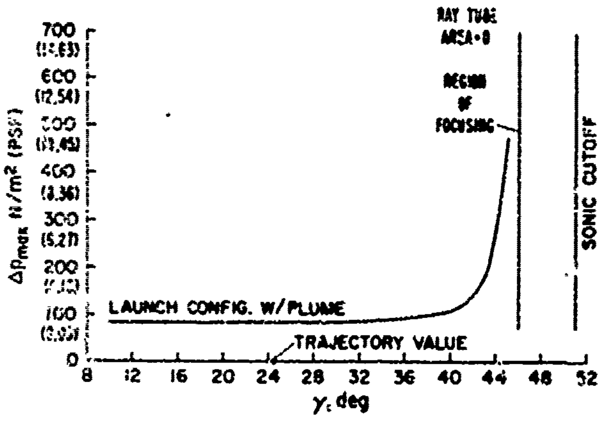


Model sketch

The two figures below, which were taken from this paper, summarize the results of this investigation. In these figures overpressure is plotted versus flight path angle, γ. The trajectory value for γ is shown by a "tick" mark on the abscissa. It can be seen that for Mach 3 the combination of flight path angle and rate of change of flight path angle produced pressure wave focussing with attendant high level of overpressure. At Mach 4 no focussing was present and the level of overpressure was approximately 2 psf.

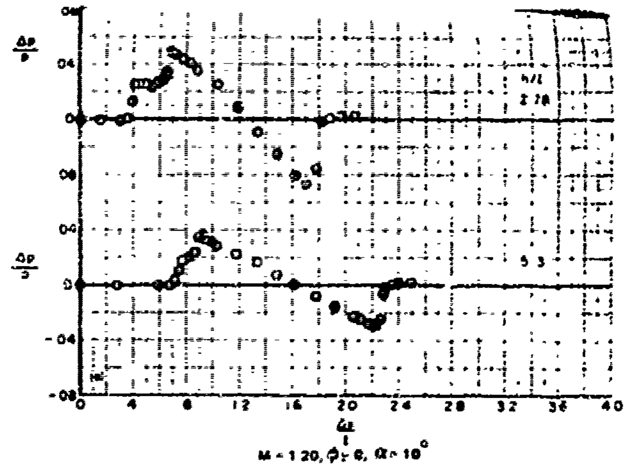


Sonic boom during ascent



Sonic boom during ascent

The sonic boom characteristics of the space shuttle orbiter during reentry were investigated in the report summarized in capsule summary SBA-14.



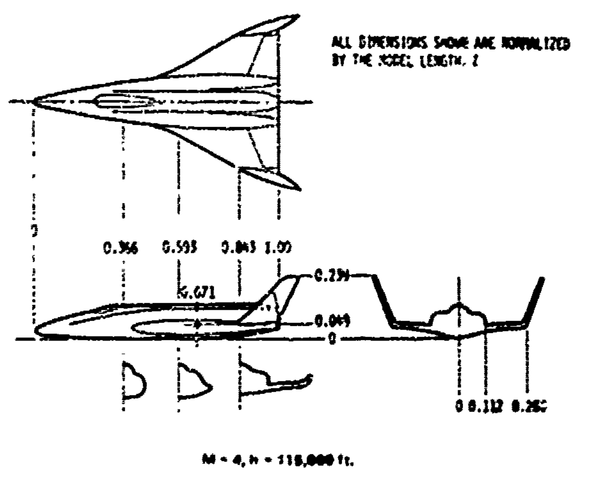
Pressure signatures

The sonic boom characteristics of a straight-wing space shuttle orbiter are evaluated and compared to those of the delta-wing orbiter in the report summarized in capsule summary SBA-14.

SBA-17
WIND TUNNEL PRESSURE SIGNATURES FOR A DELTA-WING SPACE SHUTTLE VEHICLE
Raymond M. Hicks and Joel P. Mendoza
NASA TMX-62,040, August 4, 1971

In this report sonic boom pressure signatures, measured in various wind tunnels, are presented for a model of a delta-wing space shuttle vehicle. Data are presented for Mach numbers ranging from 1.20 to 10.02, angles of attack ranging from 0 to 60 degrees and roll angles ranging from 0 to 180 degrees.

The first figure below, which was taken from this paper, shows a sketch of the model. The second figure shows typical measured pressure signatures. No extrapolations were made in the present paper to obtain far-field overpressures.

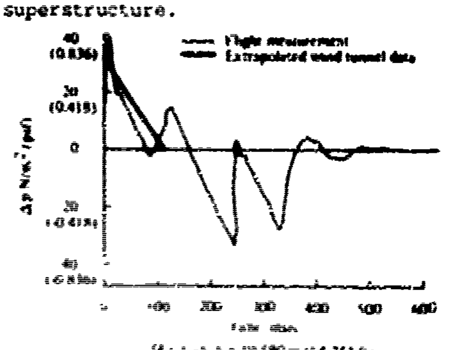


Delta-wing space shuttle

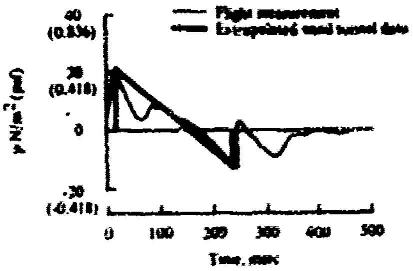
SBA-18
A WIND TUNNEL-FLIGHT CORRELATION OF APOLLO 15 SONIC BOOM
Raymond M. Hicks, Joel P. Mendoza, and Frank G. Garcia, Jr.
NASA TM-X-62111, January 1972

In the investigation described in this report, a correlation of sonic boom pressure signatures recorded during reentry of the Apollo 15 command module with wind tunnel signatures extrapolated to flight distances was made for Mach numbers of 1.16 and 4.57. The flight pressure signatures were recorded by pressure sensors located onboard ships positioned near the ground track, while the wind tunnel signatures were measured during tests of a 0.016-scale model of the command module.

The results of the correlation are shown in the two figures below, which were taken from this paper. In the first figure only the positive portion of the wind tunnel signature is shown since shock wave reflections from the floor of the wind tunnel prevented the recording of the full pressure signature at M = 1.16. At Mach 1.16 the predicted overpressure is 0.16 psf below the value actually measured on the ground (0.84 psf). The discrepancy was thought to be due to atmospheric effects. The second figure shows that the wind tunnel-flight correlation for peak overpressure at M = 4.57 was very good. The multiple shock waves exhibited by the flight pressure signatures could not be adequately explained, but it was thought that they might have been due to shock reflections from the ship superstructure.



Apollo 15 command module wind tunnel flight correlation



M = 4.57, h = 34,450 m (110,304 ft)

Apollo 15 command module wind tunnel-flight correlation

The wind tunnel measurements used in this investigation were obtained in the experiment described in capsule summary SBA-15. The actual measured pressure signatures are discussed in more depth in the report summarized in capsule summary SBA-21.

SBA-19
TU-144 DETAILS
ICAO SST Memorandum No. 40, May 23, 1972.

This memorandum gives characteristics of the Soviet SST, the TU-144. This information is given in the two tables below, which were taken from this memorandum. The first table presents a description of the aircraft itself, while the second table gives its sonic boom characteristics.

Preliminary data of the TU-144 aircraft

NN	D A T A	Dimension	Value
1.	Take-off weight	kg	18,000
2.	Max. Landing weight	kg	11,000
3.	Span	m	28
4.	Length	m	64
5.	Height	m	12.8
6.	Wing area	m^2	437
7.	No. of engines	-	4
8.	Engine type	-	HK-144
9.	Max. thrust	kg	17500 to 20000
10.	Wing configuration	-	almost "double-delta"
11.	Nose	-	down to 17°
12.	Controls	-	elevons and rudder
13.	Wing type	-	fixed
14.	Supersonic cruising flight.		
	Mach number	-	2.2 + 2.35
	Altitude	km	16 to 18
15.	Programme of climb and descent		See next column

TU-144 characteristics

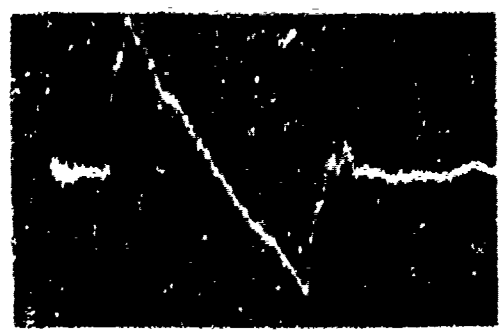
Mode	Mach	Height (km)	Weight (kg × 1000)	Peak Overpressure, max (N/m²)	Signature interval t(ms)
Climb	1.50	14.0	170	95.1	340
Cruise	2.20	17.0	150	93.1	280
Descent	1.35	16.0	111	72.5	240

Sonic boom characteristics of TU-144

The peak overpressure during cruise for the TU-144 is approximately the same as that of the Concorde (see capsule summary SBA-20).

SBA-20
MEASUREMENT OF SONIC BOOM FROM CONCORDE -002 AUSTRALIA 1972
M. E. L. Williams and M. W. Page
Australia Department of Civil Aviation R & D Report No. 896, August 1972

This report presents measurements of the sonic boom of the Concorde -002. The measurements were made during two test flights made over Australia during June 1972. The flights were made at an altitude of about 57,000 feet and at a Mach number of about 2. The results indicated that, for a signature undistorted by atmospheric turbulence, the maximum overpressure on the ground was about 1.9 psf. The figure below, which was taken from this report, shows a typical measured signature.



25 Pa/div
50 ms/div

Concorde 002 Pressure signature

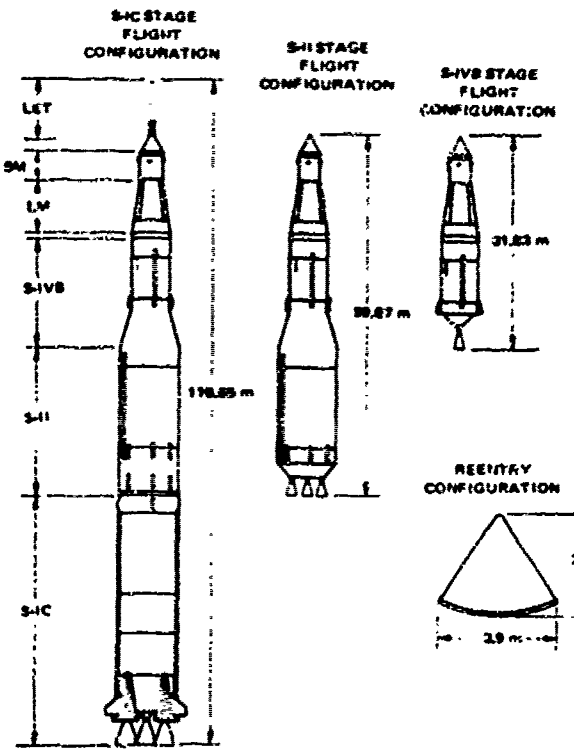
The peak overpressure during cruise for the Concorde is about the same as that of the Soviet TU-144 (see capsule summary SBA-19).

Measurements of the pressure signature of the French-assembled Concorde -001 are discussed in the paper summarized in capsule summary SBA-23. Further sonic boom characteristics of the Concorde are given in capsule summary SBA-13.

SBA-21
SONIC BOOM GROUND PRESSURE MEASUREMENTS FROM APOLLO 15
David A. Hilton and Herbert R. Henderson
NASA TN D-6950, September 1972

This paper presents sonic boom pressure signatures recorded during the launch and reentry phases of the Apollo 15 mission. The measurements were obtained along the vehicle ground track at 87 Km (47 n.mi.) and 970 Km (523 n.mi.) downrange from the launch site during ascent; and at 500 Km (270 n.mi.), 55.6 Km (30 n.mi.), and 12.9 Km (7.0 n.mi.) from the splashdown point during reentry.

The figure below, which was taken from this paper, shows the vehicle configurations during ascent and reentry. A comparison of the measured signature characteristics with those calculated using the existing sonic boom prediction techniques (see capsule summary G-25) is shown in the table below which also was taken from this paper. Possible effects of the rocket exhaust plume on ascent and the ionization sheath on descent were ignored in the calculations. Absolute overpressure estimates were not attempted for the ascent condition since it was not clear how to handle the exhaust plume. Fairly good comparisons were obtained for the measured and calculated overpressures for the descent conditions. The estimates of overall duration were generally low for the ascent conditions and high for the descent conditions. The discrepancies for the ascent flight conditions were again believed to be due to the rocket-exhaust plumes which were not properly accounted for in the estimate.



Apollo 15/Saturn V launch vehicle and reentry vehicle configurations

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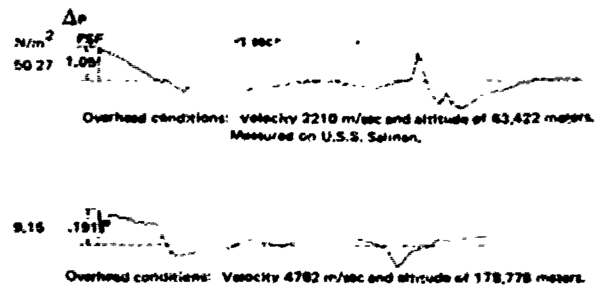
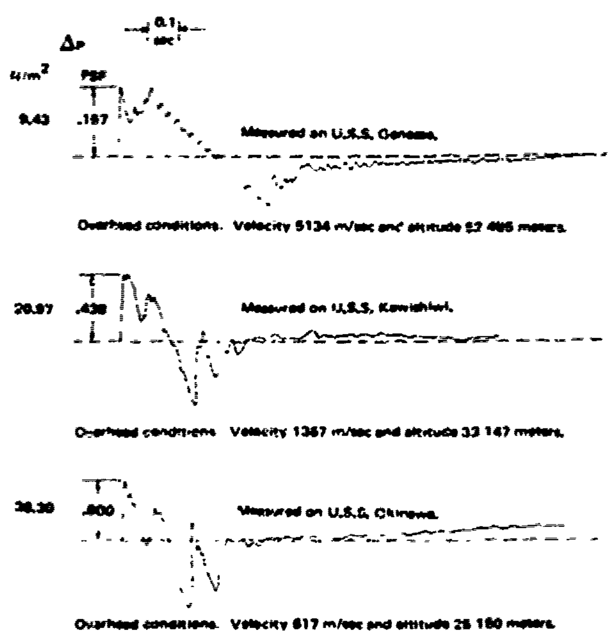
Comparison of measured and calculated signature characteristics

Measured pressure signatures during ascent are shown in the figure below which, again, was taken from this paper. The initial positive impulse was believed to be due to the spacecraft as it neared the overhead position. The positive peak occurring approximately 9 seconds after the initial pressure onset, as measured aboard the U.S.S. Salinan, was believed to be a secondary sonic boom pressure wave that was generated by the spacecraft farther up the flight track (closer to the launch site) and was due either to the curved flight path of the vehicle or its acceleration rate. The source of the secondary negative pulse in the second signature was not known. The long durations were believed to be associated with the effect of the spacecraft rocket-motor plume during ascent.



Measured sonic boom signatures during ascent

The signatures measured during the descent of the command module are shown in the figure below. The multiple shocks were thought to be due to the spacecraft itself. However, it was pointed out that reflections from objects onboard the ships could not be definitely ruled out.



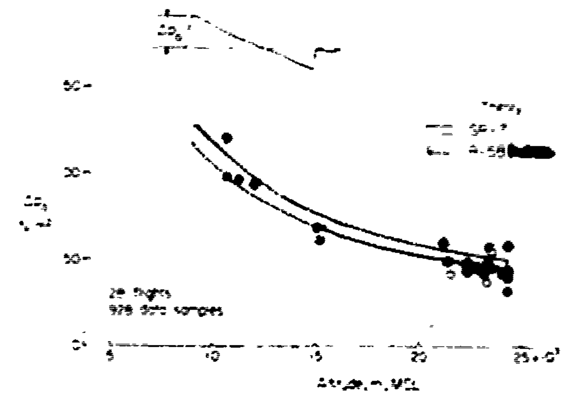
Measured sonic boom signatures during descent

Wind tunnel pressure signatures for the Apollo command module were presented in the paper summarized in capsule summary SBA-15. A correlation of wind tunnel and flight-measured signatures was made in the paper summarized in capsule summary SBA-18.

SBA-22
SONIC BOOM MEASUREMENTS FOR SR-71 AIRCRAFT OPERATING AT MACH NUMBERS TO 3.0 AND ALTITUDES TO 24384 METERS
Domenic J. Maglieri, Vera Huckel, and Herbert R. Henderson
NASA TN D-6823, September 1972

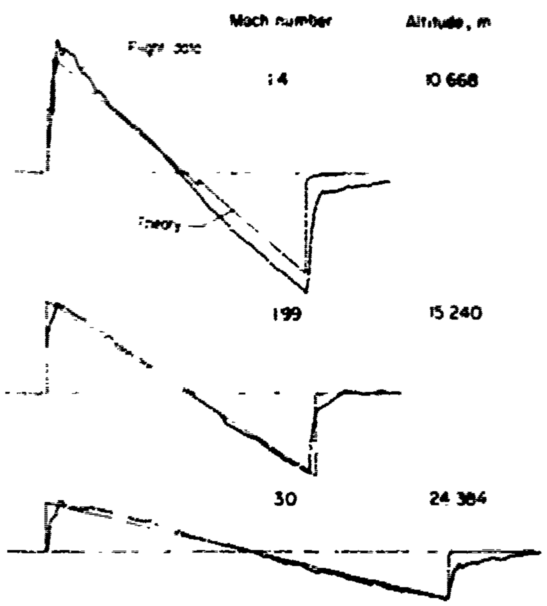
Sonic boom pressure signatures produced by the SR-71 aircraft at altitudes from 10,668 to 24,384 meters and Mach numbers 1.35 to 3.0 were obtained as an adjunct to the Edwards Air Force Base Sonic Boom Evaluation Program (see capsule summary SR-39) relating to structural and subjective response which was conducted in the 1966-1967 time period. Approximately 2000 sonic boom signatures from 33 flights of the SR-71 and two flights of the F-12 (which is of the same general type) were obtained.

A comparison of the measured and calculated variation of peak overpressure with altitude is shown in the figure below which was taken from this paper. It can be seen that the overpressure varies from about 120 N/m^2 (~2.5 psf) for flight at about 11,000 meters to about 50 N/m^2 (~1 psf) for flight at an altitude of about 24,000 meters.



Variation of peak overpressure with altitude for SR-71

The figure below shows tracings of measured and calculated pressure signatures at various altitudes and Mach numbers. It can be seen that the agreement between experiment and theory is good.



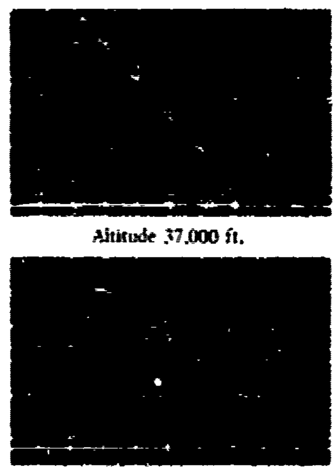
SR-71 signatures

This is the best available source for data concerning the sonic boom characteristics of the SR-71.

SBA-23
RECENT SONIC-BANG STUDIES IN THE UNITED KINGDOM
C. H. E. Warren
The Journal of the Acoustical Society of America, Vol. 51, No. 2 (Part 3), 1972, Sonic Boom Symposium, pp. 783-789

This paper summarizes the sonic boom studies conducted in the United Kingdom between 1965 and 1970. The present capsule summary is concerned only with the portion of the paper dealing with measurements of the Concorde sonic boom. For a summary of the rest of the paper see capsule summary S-46.

Measurements of the sonic boom pressure signatures of the French-assembled Concorde prototype 001 were made in December 1969 during flights at Istres, France. Four overflights were made, two at 45,000 feet and two at 37,000 feet, all at a nominal Mach number of 1.3. The figure below, which was taken from this paper, shows typical measured waveforms. It can be seen that the waveforms are basically N-waves. However, the waveform for 37,000 feet has not quite attained its far-field asymptotic shape, as evidenced by the presence of two shocks, one behind the other, at the front limb of the N. This has disappeared, however, for 45,000 feet.



Concorde-001 pressure signatures

The table below, which was also taken from this paper, shows average values of the characteristic overpressure (defined as four times the maximum impulse divided by the signature interval) and signature interval for the two altitudes. The measured values were found to agree very well with standard calculations made using the gross atmospheric conditions prevailing at the time.

Altitude	Characteristic overpressure		Signature interval
ft	N/m^2	lbf/ft^2	msec
37 000	120	2.5	254
45 000	110	2.3	275

Concorde-001 pressure signature parameters

For an illustration of the nominal peak over-pressure occurring along the entire flight path and a discussion of carpet width of the Concorde, see capsule summary SBA-13. Measurements of the ressure signatures of the British-assembled Concorde 002 are discussed in the paper summarized in capsule summary SBA-20.

13.0 OPERATIONS AND AIRPLANE PERFORMANCE

OAP-1
SONIC BOOM - LIMITATIONS ON SUPERSONIC AIRCRAFT OPERATIONS
Donald W. Patterson
Aero Space Engineering, July 1960

An attempt is made in this paper to find the optimum speed-altitude schedule for a supersonic transport or bomber, with minimum sonic boom ground disturbance as the prime consideration. The conclusion reached is that maximum altitude should be reached as soon as possible, climbing at subsonic speeds at maximum practical climb path angle. During the climb, the speed must be kept below the cutoff Mach number. No boom should be permitted to reach the ground until the aircraft has reached an altitude of 50,000 feet. As the descent penetrates the 50,000 foot level, the aircraft should be at transonic speeds.

This is a very brief analysis, and the assumption that the aircraft will not cause objectionable pressure rises on the ground for flight altitudes above 50,000 feet is very questionable. In addition, normal airplane operational considerations indicate that such a climb profile would be extremely costly in terms of airplane range and payload. (See summaries OAP-5 and OAP-8.)

OAP-2
THE SUPERSONIC TRANSPORT - REQUIRED CHARACTERISTICS OF CONFIGURATIONS
Mark R. Nichols
Paper Presented at SAE National Aeronautic Meeting, New York, New York, 1961

This paper discusses the requirements that operational constraints, such as the sonic boom, would place upon the characteristics of supersonic transport configurations. The portion of the paper dealing with the sonic boom is quite short, and only that portion of the paper will be summarized here.

The decrease of sonic boom overpressure with altitude is discussed briefly. It is then stated that, since a sonic boom with an overpressure of 1 psf resembles distant thunder and should cause negligible public reaction and a boom with an overpressure of 2 psf may begin to cause occasional minor damage, the maximum tolerable sonic boom overpressure may be in the vicinity of 1.5 psf. Using this as the criterion, it is concluded that a Mach 3 cruise condition is preferable to a Mach 2 cruise condition because the cruise altitude of the Mach 2 airplane is about 10,000 feet lower, leading to an overpressure which is 1/4 psf higher than the Mach 3 cruise.

In a later paper (see capsule summary OAP-4) Patton also speculated that lower overpressures were possible for Mach 3.0 cruise than for Mach 2.0 cruise.

This paper has two main weaknesses:

1. The conclusion that an overpressure of 1 psf is acceptable was conjecture based on a very small amount of data.

2. The manner in which the variation of overpressure with altitude was determined is very sketchy and qualitative.

OAP-3
SPECIAL CONSIDERATIONS IN OPERATION OF SUPERSONIC AIRCRAFT
J. Kenneth Power
Navigation, Vol. 8, No. 4, Winter, 1961-62

Several areas to be considered in the operation of supersonic transports, including sonic boom, are discussed in this paper. Included in the discussion are the then-current and proposed research programs, a brief treatment of sonic boom generation and propagation, and a brief discussion of subjective and structural reaction to sonic booms. It is concluded that the success of the supersonic transport will probably depend on the sonic boom characteristics of this aircraft, and that turbofan engines providing high thrust augmentation for increasing acceleration altitudes, climb angles, etc., seem highly desirable.

OAP-4
SUPERSONIC TRANSPORT DESIGN CHARACTERISTICS AND THE SONIC BOOM
R. J. Patton
IAS Paper No. 62-23, Presented at the IAS 30th Annual Meeting, New York, New York, January 22-24, 1962

The effect that sonic boom constraints have on the design characteristics of supersonic transports is discussed in this paper. The equation for sonic boom overpressure due to lift (see capsule summary G-10) is applied to a series of aircraft designed for different speeds, payloads, ranges, and powerplants, and only the cruise overpressure is considered.

It is shown that there is about 1/2 psf reduction in overpressure in going from Mach 2.0 to Mach 3.0, due to the higher cruise altitude of the Mach 3.0 airplane. In conjunction with the design range, it was found that for a thrust to weight ratio of 0.4, the overpressure increases at shorter ranges due to the fact that payload is constant while airplane size is decreasing and the powerplant is decreasing proportionately. It was also found that, for a given Mach number, the minimum takeoff weight did not correspond to the design for minimum overpressure, which implied a higher design thrust to weight ratio for sonic boom considerations than for straight economic considerations. Finally, it was found that lower wing loadings correspond to lower overpressures. It is concluded that further research on structural, propulsion, and aerodynamic improvements are just as important as a strong sonic boom research program.

The lower overpressure of Mach 3.0 cruise as compared to Mach 2.0 cruise was also pointed out in an earlier paper by Nichols (see capsule summary OAP-2).

OAP-5
THE EFFECT OF LIMIT SONIC BOOM OVERPRESSURE CLIMB PATHS ON THE SIZE AND RANGE OF A MACH 2.5 TRANSPORT
Dennis Metherell
Boeing Airplane Company, Document No. D6-4030, January 1963

The effects on airplane size and range that result from limiting the sonic boom overpressure generated during climb on a standard day are discussed in this report.

The study configuration is typical of a Mach 2.5 cruise transport designed for a payload of 25,000 lbs. and a range of 2500 NM. The gross weight varies between 293,000 lbs. at a sonic boom overpressure of 2.75 psf (structural placard) to 340,000 lbs. at a limiting overpressure of 1.6 psf; these weights correspond to the design range-payload and a landing field length restriction of 6000 ft utilizing blown flaps.

The following conclusions were reached:

1. There is a minimum value of overpressure that can be reached for any specified range-payload requirement. The particular value that can be reached depends upon the configuration's gross weight to empty weight ratio and its sonic boom characteristics.

2. The highest overpressure, $\Delta P = 2.76$ psf, comes from following a high speed structural climb placard. This approximates an optimum fuel management climb path. The lowest overpressure, $\Delta P = 1.50$ psf, requires a high alititude climb path.

3. Regardless of the design overpressure, in a practical case it will be necessary to oversize the engine airflow relative to that required for maximum range on a standard day.

4. For the high altitude climb placards needed for low overpressures, oversizing is necessary to improve the thrust margin in climb.

5. For high speed climbs and high overpressures, oversizing is necessary to reduce community noise to an acceptable level.

OAP-6

FURTHER DEFINITION OF THE SONIC BOOM PROBLEM AND ITS INFLUENCE ON SUPERSONIC TRANSPORT DESIGN, PROPULSION AND PERFORMANCE REQUIREMENTS
Herbert A. Hutchinson
AIAA Paper No. 63-230, Presented at AIAA Summer Meeting, Los Angeles, California, June 17-20, 1963

This paper discusses the effect of sonic boom constraints on supersonic transport design, propulsion, and performance requirements. The basic conclusions reached are as follows:

1. The effect of configuration on sonic boom overpressure was felt to be greater than some of the earlier references on the topic had indicated.

2. The major emphasis in propulsion study efforts should be on raising the maximum altitude limit of the engine operating envelope. This sould permit acceleration from low to high supersonic Mach numbers at high altitudes.

3. A determination of a mixed engine cycle or a thrust augmentation scheme which would permit the use of a total engine thrust to take-off gross weight ratio of approximately 0.4 and yet which would provide the capability of a climb with overpressure not to exceed 1.5 psf should be included in propulsion study efforts. If it becomes possible to obtain overpressure less than 1.5 psf during climb, it was felt that every effort should be made to produce the lowest possible overpressure consistent with good operating economics.

4. The vehicle weight and dimensions must be held to the absolute minimum necessary to accomplish the design mission.

5. Many aspects of the supersonic transport design problem (i.e., propulsion system, performance, configuration, operational usage, and economics) are very sensitive to the level of allowable sonic boom overpressure. Thus it is imperative that a limit allowable overpressure be firmly established.

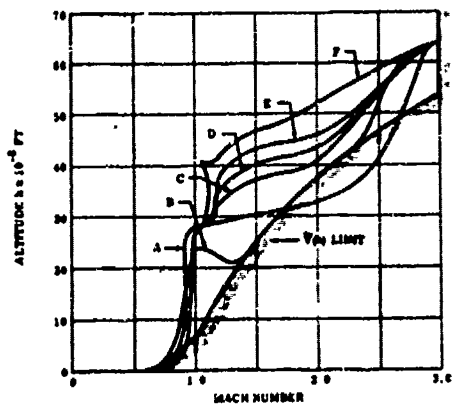
This is a good general discussion of the effect that a sonic boom constraint has on SST design.

OAP-7

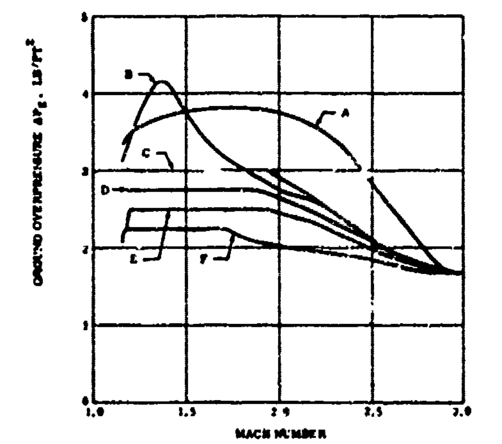
SUPERSONIC TRANSPORT CLIMB PATH OPTIMIZATION INCLUDING A CONSTRAINT ON SONIC BOOM INTENSITY
Michael Falco
AIAA Journal, Vol. 1, No. 12, December 1963, pp. 2859-2862

The effect of a sonic boom constraint on aircraft performance in the acceleration-climb portion of flight is discussed in this short note. Typical numerical solutions are presented to the problem of minimum-fuel acceleration climb from post-takeoff initial conditions to begin-cruise terminal conditions for a representative canard/delta transport configuration having a takeoff weight of 400,000 pounds.

The two figures below, which were taken from this paper, summarize the findings of this investigation. In the first figure curve A shows the minimum fuel trajectory viewed in the Mach number-altitude plane without any inequality constraints. Curve B satisfies a representative engine/airframe limit without regard to sonic boom overpressure limitations. Curves C through F illustrate those paths satisfying particular overpressure limits without engine/airframe limit constraints. The second figure shows the accompanying ground sonic boom overpressure for each of the various climb trajectories. It can be seen that trajectory F leads to the most favorable sonic boom characteristics. However, it was found that such a trajectory resulted in a 44,000 lb increase in fuel expenditure over that of trajectory B or, alternatively, a net range loss of approximately 300 statute miles.



Minimum fuel acceleration-climb profiles



Overpressure histories

An earlier study by Patterson (see capsule summary OAP-1) also led to the conclusion that a Mach number-altitude trajectory such as that of curve F would result in the most favorable sonic boom characteristics. However, no analysis of the performance penalties involved was made in that paper. A similar but more extensive study than the one of the present paper was made by Metherell (see capsule summary OAP-5).

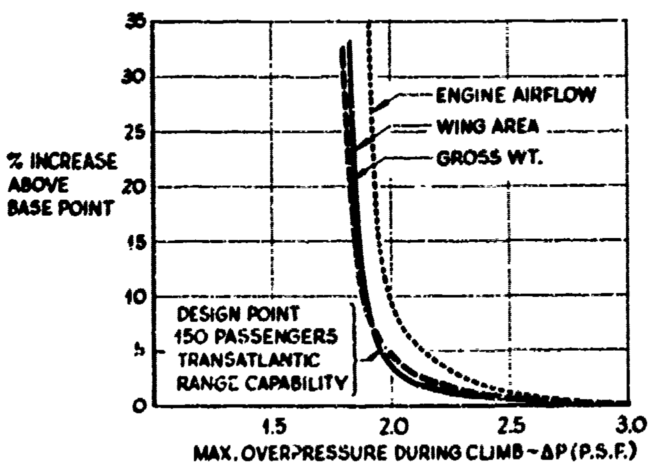
This is a good concise discussion of the penalties in airplane performance resulting from sonic boom constraints.

OAP-8
EFFECT OF SONIC BOOM ON SUPERSONIC TRANSPORT DESIGN AND PERFORMANCE
Edward J. Kane and Armand Sigalla
Paper Presented at Fifth Conference on Applied Meteorology of the American Meteorological Society: Atmospheric Problems of Aerospace Vehicles, Atlantic City, New Jersey, March 2-6, 1964. Also, Boeing Airplane Company Document D6-8614, February 1964

This paper discusses the effect of sonic boom overpressure limits on the design and performance of a supersonic transport. Possible methods of reducing the sonic boom by configuration tailoring and the effect of this on performance are also described.

In the first part of the paper a general discussion is given of the various influences, such as airplane characteristics, Mach number, etc., which affect the sonic boom strength. A brief discussion of atmospheric effects on sonic boom propagation and the results of community response studies to determine maximum acceptable sonic boom overpressure is then given.

The discussion of the first part of the paper forms the basis for the treatment in the last portion of the paper of the effect of overpressure limit on design. The figure below shows the effects of sonic boom in climb on the takeoff gross weight, engine airflow, and wing area of an airplane which flies a given distance with a given payload. This figure shows that eventually a value of ΔP in climb is reached where any further reduction in sonic boom intensity would be impractical. From this point on, further reductions in the sonic boom in climb for the basic airplane could only be accomplished by reducing either the payload or the range, or both. It is pointed out that configurations are usually selected so that they lie at the "knee" of gross weight--overpressure curves. In cases where the design point lies at an overpressure which is above the acceptable limit, the knee of the curve may be shifted to a lower value with some careful modifications to the design of the basic configuration.



Design penalties

A brief discussion is then given of the tradeoffs involved in modifying a configuration to lower its sonic boom, since this often results in increased drag. The main point brought out is that care must be taken not to compromise other design features of the airplane in order to obtain lower sonic boom overpressures.

This is a good discussion of the problems the airplane designer must overcome in meeting sonic boom constraints. The subject coverage is complete and concise.

OAP-9
THE INFLUENCE OF SONIC BOOM CONSTRAINTS ON SST DESIGN AND OPERATION
R. L. Foss
Lockheed Aircraft Corporation, Report No. LR 20197, November 11, 1966

This report presents the results of a parametric study conducted by Lockheed concerning the effect of sonic boom constraints on SST design and operation. This study consisted of three main parts. The first part examined the effect on the Lockheed L-2000-7 SST (characteristics are not given in this report) of completely removing sonic boom constraints. The second part examined the effect on the L-2000-7 of making the sonic boom constraints more stringent. The third part of the report examined the feasibility of a no-boom supersonic transport.

The results of the study concerning the effects of completely removing the sonic boom constraints indicated that no gains in the payload range capabilities or economics would result if the sonic boom allowances were relaxed. The 2.5 psf climb overpressure produced by the L-2000-7 airplane concept did not reflect any performance or economic compromise. Although relaxation of the boom restriction would allow for greater freedom in the choice of transonic acceleration altitudes, the study showed that the lower acceleration altitudes and the decrease in fuel weight is more than offset by the added structural weight required. Therefore, no gains in payload were found to be possible.

The second part of the study examined the influence on the design, operation, and economics of a fixed-wing domestic range SST if the cruise sonic boom had to be reduced to the order of 1 psf. The emphasis here was placed on obtaining a low boom signature airplane design, and a configuration that could perform the desired domestic mission economically at the lightest possible weight and flying at the most advantageous cruise altitudes. It was found that, even with optimistic assumptions made with regard to foreseeable advances in arrow wing cruise lift/drag ratio technology, the reductions in airplane gross weight needed to reduce sonic boom overpressures to 1.0 to 1.2 psf caused significant reductions in payload and made the airplane economically unfeasible.

The last part of the study consisted of a brief investigation of the feasibility of operating a supersonic transport in the low supersonic regime below cutoff Mach number so that no sonic boom reaches the ground. This study revealed two important results. First, it was found that such a design would be operating in a very uneconomical flight regime because the drastically reduced lift/drag ratio associated with low supersonic Mach number flight would severely compromise the cruise efficiency of the airplane. Secondly, it was concluded that, due to variable atmospheric effects, the shock waves generated by the aircraft would very frequently reach the ground resulting in intensified sonic booms. On the basis of these findings it was concluded that a no-boom SST did not appear to be feasible.

This is an excellent report. However, the only aspect of the sonic boom considered in these parametric studies (as was the case in similar previous reports--see capsule summary OAP-5, for example) is the bow shock overpressure. It has been shown in many psychological studies (see capsule summary HRSC-16, for example) that rise time is just as important as overpressure in determining human reaction to sonic booms. Thus modifying an aircraft configuration with only overpressure considerations in mind may not result in a pressure signature that is more acceptable to the public.

OAP-10
ASSESSMENT OF SONIC-BOOM PROBLEM FOR FUTURE AIR-TRANSPORT VEHICLES
Donald D. Baals and Willard E. Foss, Jr.
Proceedings of the Sonic Boom Symposium, The Journal of the Acoustical Society of America, Vol. 39, No. 5, Part 2, 1966, pp. S73-S80

In this paper modifications to the mission profile and aircraft design techniques are evaluated with regard to sonic boom constraints. An analysis concerning potential boom levels is made of an intermediate-range, domestic, supersonic transport optimized for low sonic boom. The discussion also treats future aircraft, such as the hypersonic transport and the ballistic transport, concerning their sonic boom characteristics.

The basic points made in this paper are as follows:

1. Careful aircraft design is required to meet sonic boom overpressure goals without incurring excessive performance penalties. The specification of an unnecessarily low required overpressure could effectively preclude the development of any supersonic transport.

2. If the community reaction encountered in initial operation proves to be more adverse than expected, serious or even prohibitive reductions in supersonic range could result from altering operational procedures to reduce sonic boom levels.

3. A small domestic SST may be able to atain overpressure levels approaching 1 psf.

4. Cruise sonic boom levels for future hypersonic aircraft appear to be less critical than for typical supersonic cruise aircraft of the same weight due to the increased cruise altitude. However, the transonic acceleration phases will still be a critical problem for hypersonic aircraft.

As in similar previous studies (see capsule summary OAP-9, for example) the main drawback of this investigation is that overpressure is the only pressure signature characteristic considered.

OAP-11
AIRPLANE SIZE AND STAGING EFFECTS ON SST CRUISE SONIC BOOM
John B. Whitlow, Jr.
NASA TND-4677, July 1968

This report presents the results of an analytical study made to determine the performance requirements and economic penalties involved in reducing the cruise sonic boom of various sizes of a domestic-range supersonic transport. [illegible] attempt was made to reduce the climb sonic boom since

climb occurs over a relatively short range and can perhaps be scheduled over sparsely populated areas. A similar study was made to determine the improvement in cruise sonic boom that might be obtained by use of a two-stage vehicle having stage separation just before the start of cruise.

The main findings of this investigation were as follows:

1. For unstaged airplanes in the 200-passenger category, reductions up to 10 percent in initial cruise boom can be obtained at the expense of approximately equal percentage increases in direct operating cost (DOC) by beginning cruise at higher-than-payload-optimum altitudes. Greater reductions in sonic boom (up to a maximum of about 39 percent) can be obtained for this particular configuration with size and weight reductions but only at the expense of severe DOC penalties (about a five-fold increase).

2. When a comparison is made between staged and unstaged vehicles of the same payload capacity, the results of this study show that staging will provide a reduction of only about 5 percent in initial cruise boom. Staging thus offers little potential for boom reduction even though the technical problems and additional expense associated with it were ignored here.

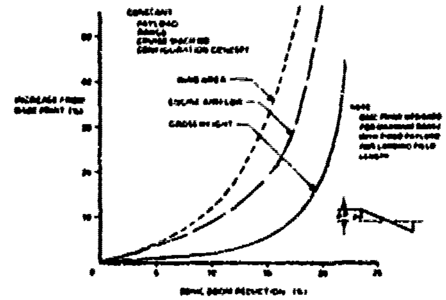
3. The higher levels of performance that can be expected with evolutionary improvements in the design of airframes and kerosene-fueled engines will probably lower somewhat the economically attainable levels of cruise sonic boom. To completely solve the problem, however, a new approach or significant technological advance is required.

This paper does an excellent job of demonstrating the severe performance penalties involved in significantly reducing sonic boom levels by only using operational means. The main weakness of this paper as in most similar previous studies (see capsule summary OAP-9, for example) is that the only characteristic of the sonic boom pressure signature considered is the overpressure.

OAP-12
SONIC BOOM CONSIDERATIONS IN AIRCRAFT DESIGN
C. S. Howell, A. Sigalla, and E. J. Kane
AGARD Conference Proceedings No. 42, Aircraft Engine Noise and Sonic Boom, May 1969, pp. 30-1 thru 30-7

This paper is concerned for the most part, with sonic boom minimization concepts. For a summary of that portion of the paper the reader is referred to capsule summary M-39. Only the brief portion of the paper dealing with the effects of sonic boom reductions on airplane performance will be summarized here.

The figure below shows the wing area and engine size increases and resulting gross weight increases required to climb to altitudes higher than optimum for range in order to reduce sonic boom. Payload, range, and landing field length requirements were held constant for these data. It can be seen that sonic boom reductions greater than 15 to 20 percent are prohibitive.



Effect of sonic boom overpressure on airplane design

The results shown in the figure above emphasize the fact that in order to achieve significant reductions in sonic boom without severely penalizing aircraft performance it will be necessary to use some other means than merely increasing the cruise altitude.

14.0 SURVEY PAPERS

S-1
THEORETICAL INVESTIGATIONS OF SONIC BOOM PHENOMENA
R. A. Struble, C. E. Stewart, E. A. Brown, and A. Ritter
Wright Air Development Center, WADC Technical Report 57-412, ASTIA Document No. 130883, August 1957

This report presents a very extensive discussion of nearly all aspects of sonic boom theory as of 1957. The following topics are included in the discussion: (1) linear theory; (2) nonlinear effects; (3) atmospheric effects; (4) steady state effects; (5) non-steady state effects; (6) effects of body shape; (7) shock wave reflection; (8) response of structures; and (9) effects of multiple bodies. This is an excellent summary of the state of the art of sonic boom theory as of 1957.

S-2
THE SHOCK-WAVE NOISE PROBLEM OF SUPERSONIC AIRCRAFT IN STEADY FLIGHT
Domenic J. Maglieri and Harry W. Carlson
NASA MEMO 3-4-59L, April, 1959

Data are presented in this report concerning the nature of the sonic boom problem, the significant variables involved and the manner in which airplane operation may be affected. Flight test data are given, and a comparison with available theory is made. An attempt is also made to correlate the subjective reactions of observers and some associated physical phenomena with the pressure amplitudes during full-scale flight.

As part of the discussion of the theory, the following equation is given for the bow shock overpressure of an N-wave:

$$\Delta P = K_1 K_2 \left(\frac{\sqrt{P_a P_o}}{y^{3/4}} \right) (M^2-1)^{1/8} \left(\frac{1}{\ell/d} \right) \ell^{3/4}$$

where K_1 = ground reflection coefficient
K_2 = body-shape constant
ℓ = body length
ℓ/d = body fineness ration
M = airplane Mach number
P_a = ambient pressure at altitude
P_o = ambient pressure at ground level
and y = distance normal to flight path.

This equation is a form of Whitham's asymptotic equation (see capsule summary G-3), and it was used in several subsequent investigations. A comparison of flight test data from an F-101 with the results calculated using this equation showed fairly good agreement.

A table is given, based upon early test results, which gives the response of people and structures to various sonic boom intensities. According to this table, booms of 0.1 to 0.3 psf are not objectionable, booms of 0.3 to 1.0 psf are tolerable, booms of 1.0 to 3.0 psf are objectionable, booms of 3.0 to 10.0 psf cause damage to large plate-glass windows, and booms of 10.0 to 30.0 psf cause damage to small barracks-type windows.

In conjunction with airplane operations it is concluded that the boom pressure will be most severe during the climb and descent phases of the flight plan. It is pointed out that the boom pressures during the climb, cruise, and descent phases can be minimized by operating the airplane at its maximum altitude consistent with its performance capabilities.

This is a good, concise review of several aspects of early sonic boom theory.

S-3
SOME ASPECTS OF SHOCK-WAVE GENERATION BY SUPERSONIC AIRPLANES
G. H. Jordan
AGARD Report 251, September 1959

This report summarizes some of the available theoretical and experimental sonic boom investigations that had been conducted as of 1959. Most of the conclusions reached in this report were later shown to be incorrect.

S-4
EXPERIENCE OF SUPERSONIC FLYING OVER LAND IN THE UNITED KINGDOM
T. H. Kerr
AGARD Report 250, September 1959

This report presents a brief discussion of the results of supersonic flight tests conducted over the United Kingdom using the Fairy Delta 2. The discussion summarizes the restrictions placed on such supersonic flights over land, the instrumentation used to measure the sonic boom intensities and the damage and physiological sensations caused by sonic booms. The discussion of each of these topics is very general and brief.

S-5
SONIC BOOM
A. H. Zonars
The Navy Civil Engineer, December 1960, pp. 21-23

This paper presents a general discussion of the factors involved in the investigation of sonic boom damage complaints. The topics touched upon include the generation and propagation of sonic booms, response of structures, technical investigative techniques, and reporting and expression of technical opinion.

S-6
SOME CONSIDERATIONS OF SONIC BOOM
J. Kenneth Power
Federal Aviation Agency, Office of Plans, May, 1961

This paper presents a discussion of several aspects of the sonic boom problem. The following topics are included in this discussion: (1) Whitham's theory; (2) sonic boom-volume critical; (3) sonic boom-lift critical; (4) effects of temperature and wind; (5) cutoff Mach number; (6) lateral spread; (7) combined volume and lift theory; (8) comparison of theory and flight-test results; (9) comparison of sonic booms and point source explosions; (10) structural reaction; and (11) human reaction.

This is a good summary of the state of the art of sonic boom theory as of 1961.

S-7
A REVIEW OF THEORETICAL AND EXPERIMENTAL INFORMATION RELATING TO THE SONIC BOOM
H.H.C. Lyster
National Research Council of Canada, Aeronautical Report LR-313, September 1961

In this report a review of sonic boom theory is presented and comparisons with experimental data are made. The topics discussed include Whitham's theory, cutoff Mach number, acceptable overpressure limit, and the effects of temperature and wind gradients.

Whitham's theory (see capsule summary G-3) is discussed briefly in conjunction with sonic boom volume theory, and sonic boom lift theory is also touched upon. From a comparison of experiment and theory it is concluded that the sonic boom volume theory is a valid approximation to the total overpressure for flight altitudes up to the tropopause.

In conjunction with the cutoff Mach number discussion, an expression is derived which related the cutoff Mach number for level flight to that of climbing flight. Lina, et al. derived a similar expression in an earlier paper (see capsule summary TM-2).

S-8
SONIC BOOM
Herbert A. Wilson, Jr.
Scientific American, Vol. 206, No. 1, January 1962, pp. 36-43

This is an introductory-type article dealing with sonic boom generation, propagation, and minimization. The concepts of shock formation, refraction of shock waves by the atmosphere, and cutoff Mach number are explained in a very straightforward manner, relying heavily on the use of illustrations. In conjunction with the discussion of sonic boom minimization, it is concluded that a breakthrough that will eliminate sonic boom as a problem seems most unlikely. However, by careful design of the airliner, with special consideration given to configuration and structure and possibly an extra margin of engine performance, it may be feasible to keep the booms from reaching the ground at an objectionable intensity.

S-9
SONIC BANG AND ITS PROBLEMS
S. M. Shankar
H.A.L. Technical Society Digest, Vol. 2, 1962, pp. 35-37

A very brief review of sonic boom generation, propagation, and minimization is presented in this paper. The topics touched upon include: (1) boom intensity due to volume; (2) boom intensity due to lift; (3) cut-off Mach number; and (4) the use of aerodynamic interference to partially suppress the boom due to lift.

S-10
SONIC BOOM AND COMMUNITY RELATIONS
J. K. Power and George Bates
Paper Presented at National Aero-Nautical Meeting, Washington, D.C., April 8-11, 1963

This paper presents a review of some preliminary accomplishments by the FAA and NASA in generating working methods for predicting the strength and location of sonic boom shock waves, in determining the effects of sonic booms on light aircraft, and determining community tolerance to various levels of sonic boom intensity. The following conclusions are reached as a result of this review:

1. The general theory for prediction of sonic boom overpressures is in good agreement with available data.

2. With the range of overpressures resulting from a commercial supersonic transport, no ground structural damage will result.

3. Overpressures up to 20 psf will not cause damage to light aircraft.

4. Sonic booms will cause no physiological harm to humans.

5. Sonic boom limits must be considered in initial aircraft design.

6. Aircraft operational procedures can minimize ground overpressures.

S-11
DEFINING THE SONIC-BOOM PROBLEM
Herbert A. Hutchinson
Astronautics and Aerospace Engineering, Dec. 1963, pp. 56-61

A review is presented in this paper of the concepts involved in designing supersonic aircraft to produce sonic booms that are more acceptable to the public. Sonic boom generation theory and the effects of sonic booms on people and structures are discussed briefly. The results of a study conducted at the USAF Aeronautical Systems Division concerning the overpressures of various supersonic transport configurations are then discussed. The following conclusions were reached as a result of this study.

1. In order to verify sonic boom prediction methods, additional flight test data using a vehicle and weight similar to the supersonic transport category were felt to be necessary.

2. Significant reduction in overpressure was felt to be possible through careful design.

3. Major emphasis in propulsion study should be placed on raising the maximum altitude limit of the engine-operating envelope to permit acceleration from low- to high-supersonic Mach numbers at high altitudes.

4. Vehicle weights and dimensions must be held to the absolute minimum required to accomplish the design mission.

5. Every effort should be made to achieve the lowest possible overpressures consistent with good operating economics.

S-12
FACTORS AFFECTING COMMUNITY ACCEPTANCE OF THE SONIC BOOM
Harvey H. Hubbard and Domenic J. Maglieri
NASA TMX-905, Proceedings of NASA Conference on Supersonic-Transport Feasibility Studies and Supporting Research, December 1963, pp. 399-412

A discussion is presented in this paper of sonic boom ground exposure levels for military operations and the manner in which these exposures are affected

by the atmosphere and by aircraft maneuvers. Brief remarks are included about various operations for which some response information had been obtained. It is concluded that experience with military aircraft was in the range of overpressure of interest but was otherwise not definitive enough for making a quantitative evaluation of the sonic boom problem.

S-13
NOISE AND SONIC BOOM CONSIDERATIONS IN THE OPERATION OF SUPERSONIC AIRCRAFT
Harvey H. Hubbard and Domenic J. Maglieri
ICAS Paper No. 64-58, Presented at the Fourth Congress-UNESCO Building, Paris, France, August 24-28, 1964

In this paper the nature of the community noise problem is reviewed and is evaluated particularly for initial climbout, landing approach, and ground operations. Also mentioned is the noise-induced structural response problem during takeoff and cruise. Discussions are given of sonic boom ground overpressure exposures for supersonic flight operation of the then-current aircraft and the manner in which these exposure are affected by the atmosphere and by aircraft maneuvers. Brief remarks are included about various operations for which some sonic boom community response information had been obtained and for which building response was noted to be an important factor.

It was concluded that, although the physical nature of the sonic boom problem was fairly well understood, some of its effects, particularly on communities, were still not well defined.

S-14
THE NATURE OF THE SONIC BOOM
H. H. C. Lyster
Materials Research and Standards, Vol. 4, No. 11, November 1964, pp. 582-587

This paper presents a general discussion of sonic boom theory. The topics discussed include: (1) generation; (2) relation of aircraft parameters to boom intensity; (3) atmospheric effects; (4) cut-off Mach number; (5) ground reflection factor; and (6) focusing effects.

S-15
SONIC BOOM EXPOSURES DURING FAA COMMUNITY-RESPONSE STUDIES OVER A 6-MONTH PERIOD IN THE OKLAHOMA CITY AREA
David A. Hilton, Vera Huckel, Roy Steiner, and Domenic J. Maglieri,
NASA TND-2539, December 1964

The purpose of this paper is to document the sonic boom pressure exposures during the Oklahoma City sonic boom experiments, which were carried out from February 3, 1964 to July 30, 1964. Data are tabulated for each flight so that they may be correlated with information generated by other organizations which participated in this program. Also included are analyses of some specific sets of data such as categorizations of waveforms and statistical breakdowns of overpressures and positive impulses. These analyses led to the following conclusions:

1. Wide variations in ground signature were observed with corresponding wide variations in the peak overpressure and to a lesser degree, variations in the positive impulse function.

2. Variations in overpressure and impulse may be represented by a log normal distribution over the significant ranges.

3. One percent of the measured overpressures equaled or exceeded the predicted values by a factor of 1.5 to 3.0 depending on the distance relative to the ground track; the larger factor was associated with the larger distances and with the lower predicted value.

4. One percent of the measured positive impulse values equaled or exceeded the predicted values by a factor of about 1.2 and 2.0 depending on the distance from the ground track, the large factor being associated with the larger distances and with the lower predicted value.

5. Measurements at several points for a given flight show also a variation in wave shape as a function of distance in the direction of flight. An orderly progression of wave shape is suggested by the data from a highly peaked wave at one point to a rounded-off wave at another and vice versa.

6. Measured pressure signatures inside of a building were lower in amplitude and longer in duration than the corresponding outside pressure signatures and were dominated by frequency components corresponding to the principal vibration modes of the building.

7. The levels of the pressure inside of a building in the range of frequencies 100 to 5,000 cps are about 30 dB lower than those in the range 0.1 to 5,000 cps; thus, an inside observer is subjected to strong pressure variations in the subaudible range and relatively weak pressure variations in the audible range.

8. For equal outside peak overpressure, peak pressures inside a residential-type structure were greater for a longer wave length.

9. Inside peak pressures were found to correlate well with variation in the positive impulse function of the outside pressure signature. For a given wave length they did not vary appreciably for marked variations in the wave shape.

This is a good survey of some of the general findings of the Oklahoma City tests. For a discussion of the specific results of the community response studies and structural response studies the reader is referred to capsule summaries HRSC-14 and SR-12, respectively. For a discussion of the results concerning sonic boom propagation, the reader is referred to capsule summary P-42

S-16
UNITED STATES SUPERSONIC TRANSPORT DEVELOPMENT PROGRAM SONIC BOOM AND NOISE RESEARCH
J. K. Power
Society of Automotive Engineers, Paper No. 650215, Presented at National Aeronautic Meeting, Washington, D.C., April 12-15, 1965

This paper presents a brief review of sonic boom generation theory and of the results of the sonic boom programs conducted at Oklahoma City (see capsule summary S-15) and White Sands Missile Range, New Mexico (see capsule summary SR-16). This is a good, concise summary of these studies.

S-17
PREDICTION OF AIRPLANE SONIC-BOOM PRESSURE FIELDS
Harry W. Carlson, F. Edward McLean and Wilbur D. Middleton
NASA Langley Research Center, NASA SP-83 Conference on Aircraft Operating Problems, May 10-12, 1965, pp. 235-244

This paper presents a discussion of the sensitivity of supersonic transport design and operation to sonic boom considerations and shows the necessity for a study of these problems early in the development program. Methods of predicting pressure signatures are outlined and examples of the correlation of these estimates with wind tunnel and flight measurement are shown. Estimates of sonic boom characteristics for a representative supersonic transport show that in the critical transonic acceleration portion of the flight, overpressures somewhat lower than estimated by use of the far-field assumptions may be expected. Promising design possibilities for the achievement of further overpressure reductions are explored.

S-18
SIGNIFICANCE OF THE ATMOSPHERE AND AIRCRAFT OPERATIONS ON SONIC-BOOM EXPOSURES
Domenic J. Maglieri and David A. Hilton
NASA Langley Research Center
NASA SP-83, Conference On Aircraft Operating Problems, May 10-12, 1965, pp. 245-256

The information of this paper is in the form of a status report on the state of knowledge of sonic boom phenomena, dealing first with the pressure buildups in the transonic speed range and with the lateral extent of the pattern in steady flight for quiescent atmospheric conditions. There are also discussions of flight test studies relating to atmospheric dynamic effects on the sonic boom signatures, and finally brief discussions of the significance of signature shape on the response of people and structures.

The following conclusions were reached as a result of this review:

1. The acceleration and lateral-spread phenomena were felt to be fairly well understood and predictable.

2. Variations in the sonic boom signature as a result of the effects of the atmosphere can be expected during routine operations.

3. Very similar variations in pressure signatures were noted for both fighter and bomber aircraft.

4. The greatest questions were felt to exist in the area of community acceptance of sonic booms.

S-19
SONIC BOOM
E. J. Richards
Science Journal, Vol. 1, May 1965, pp. 46-51

This paper presents a review of the sonic boom problem. Topics included in the review are: (1) response of the human ear to various noise levels; (2) sonic boom generation; (3) structural response; and (4) human response. The discussion in each of these areas is very general and brief.

S-20
SONIC BOOM RESEARCH AND DESIGN CONSIDERATIONS IN THE DEVELOPMENT OF A COMMERCIAL SUPERSONIC TRANSPORT (SST)
Thomas H. Higgins
Paper Presented at the Seventieth Meeting of the Acoustical Society of America, St. Louis, Missouri, November 3, 1965

A short history of sonic boom research and related operational considerations in the development of a commercial supersonic transport is presented in this paper. The two sonic boom programs conducted at Oklahoma City (see capsule summary S-15) and at the White Sands Missile Range (see capsule summary SR-16) are discussed and a brief summary of the findings of these programs is presented.

S-21
THE SONIC BOOM
Harry W. Carlson and F. Edward McLean
International Science and Technology, Vol. 55, July 1966

This paper presents a very general discussion of the factors involved in the generation, propagation and minimization of sonic booms.

S-22
NATURE OF THE SONIC BOOM PROBLEM
Harvey H. Hubbard
The Journal of the Acoustical Society of America, Vol. 39, No. 5, Part 2, 1966, pp. S1-S9

A general review of the various factors involved in the sonic boom problem is presented in this paper. Included in the discussion are the following topics: (1) aircraft design; (2) aircraft operation; (3) atmospheric effects; (4) lateral extent; (5) N-wave frequency spectrum; (6) loadings on buildings; (7) ground motions; (8) effects on other aircraft; and (9) human response. The discussion of each of these topics is very brief.

S-23
EXPERIENCE IN THE UNITED KINGDOM ON THE EFFECTS OF SONIC BANGS
C. H. E. Warren
The Journal of the Acoustical Society of America, Vol. 39, No. 5, Part 2, 1966, pp. S59-S64

This paper summarizes the results of various flight test studies that were conducted in the United Kingdom during the 1960-65 time period. The exercises summarized are the following: (1) Exercise Crackerjack; (2) Exercise Firecracker; (3) Exercise Napoleon; (4) Exercise Yellowhammer; and (5) Exercise Westminster.

Exercise Crackerjack consisted of a series of demonstrations of the sonic boom intensities that would result from civil supersonic flight. These demonstrations were made from July 1961 to July 1963 to audiences composed mainly of officials of the ministry of aviation. The booms were generated by Lightning aircraft in straight, level, and steady flight and by the firing of pairs of explosive charges. Measurements were made of the physical characteristics of the sonic booms, and the reactions of the audience to the booms were obtained. The reader is referred to capsule summary HRSC-27 for more information on this exercise.

Exercise Firecracker consisted of a single demonstration of booms of an intensity nominally greater than those that would be expected from civil supersonic aircraft to about a dozen officials of the Ministry of Aviation. All booms were simulated by the firing of pairs of explosive charges. Measurements of the intensity of the simulated booms was made both indoors and outdoors, and the opinions of the audience were obtained.

Exercise Napoleon consisted of the measurement of the intensities of sonic booms resulting from Lightning aircraft operations over the south coast resort of Lyme Regis during April and May of 1963. The boom intensities were measured in various typical British domestic interiors, as well as outdoors.

Exercise Yellowhammer was a study of the subjective reaction of a small community (280 people) to a 14-week program of simulated sonic booms made by the firing of pairs of explosive charges. The study was conducted during the summer of 1963.

Exercise Westminster was a sonic boom demonstration made in April 1965 to Members of Parliament, representatives of local government, the Press, and representatives from the Ministry of Aviation. There were 8 actual booms generated by Lightning aircraft, 10 simulated booms generated by firing pairs of explosive charges, and 4 fly-overs of a subsonic jet resulting in a noise level of 110 PNdB. Measurements were made of the boom characteristics, and the opinions of the observers were obtained. The reader is referred to capsule summary S-28 for further details of this exercise.

The results of the above studies are summarized, and it is concluded that the findings in the United Kingdom on ground reflection effects, comparison with theory, statistical variation, and indoor intensity are in broad agreement with the findings of studies that have been conducted in the United States. It was felt that the subjective studies, although smaller in scale than those conducted in the United States, were complementary, the main contribution being in work concerned with determining the subjective intensity of sonic booms.

This is an excellent summary of early flight-test research in the United Kingdom. A later paper by Warren (see capsule summary S-46) summarizes the sonic boom studies conducted in the United Kingdom from 1965 to 1970.

S-24

THE NATURE, MEASUREMENT, AND CONTROL OF SONIC BOOMS

Harvey H. Hubbard and Domenic J. Maglieri

Institute of Electrical Engineers Conference Publication, Presented at Conference on Acoustic Noise and Its Control, London, No. 26, Jan. 1967, pp. 46-49

This is a brief, general discussion of the basic concepts underlying the generation, propagation, and measurement of sonic booms, and the response of people to booms.

S-25

SONIC BOOM AND THE SST

Jim R. Thompson and John E. Parnell

Aircraft Engineering, March, 1967, pp. 14-18

A broad review of the sonic boom problem is presented in this paper. The topics discussed include: (1) basic concepts of sonic boom generation; (2) minimization; (3) effects of varying flight profile; (4) human response; (5) the Lockheed sonic boom simulator (see capsule summary SM-6; and (6) structural response.

S-26

A SURVEY OF SONIC BOOM COMMUNITY OVERFLIGHT PROGRAM OVERPRESSURE DISTRIBUTION, COMMUNITY REACTION, AND MATERIAL FAILURE DATA RELATED TO THE SUPERSONIC TRANSPORT

Thomas H. Higgins

Federal Aviation Administration Paper, April 7, 1967

A discussion is presented in this paper of the probability of the Boeing SST concept, the B-2707, causing human annoyance and structural damage. A survey of the results of major overflight programs concerning structural response and human response to sonic booms is made, and the results of this survey are used in conjunction with the calculated sonic boom characteristics of the B-2707 to arrive at the following conclusions:

1. The B-2707-100 SST would generate overpressures during cruising flight of 4.4 psf under the flight track only one time in ten thousand as a result of the statistical variation of atmospheric effects.

2. Overpressures of 5.2 psf under the flight track would be generated one time in ten thousand during transonic acceleration and climb.

3. Major city supersonic overflight programs have generated community reaction complaint data which occur one time in one hundred thousand.

4. Representative building materials--plaster on wood lath, gypsum board (old), bathroom tile (old), damaged suspended ceiling (new), and stucco (new) will experience minor damage at overpressure values ranging from 3.3 to 5.0 psf less than one time in ten thousand.

5. Window glass of various sizes and thicknesses will fail at overpressures ranging from 1.0 to 5.0 psf with the chance for a slight crack occurring less than one time in one hundred thousand.

Based on these results, several recommendations for future studies were made.

This paper presents a good discussion of the statistical likelihood of a typical SST causing structural damage.

S-27
BRIEF REVIEW OF THE BASIC THEORY
Wallace D. Hayes
NASA SP-147, Sonic Boom Research, 1967, pp. 3-7

A brief review is presented in this paper of sonic boom generation, propagation, and minimization theory. Included in this discussion are the following topics: (1) geometrical acoustics; (2) sound rays; (3) ray tube areas; (4) age variable; (5) supersonic area rule; (6) Blokhintzev invariant; (7) Whitham's theory; (8) nonlinear effects; and (9) volume and lift effects.

S-28
PHYSICAL CHARACTERISTICS OF THE SONIC BANGS AND OTHER EVENTS AT EXERCISE WESTMINSTER
D. R. B. Webb and C. H. E. Warren
Aeronautical Research Council, R. & M. No. 3475, 1967

Exercise Westminster consisted, primarily, of a sonic boom demonstration conducted on April 21, 1965. The demonstration was staged mainly for Members of Parliament, but also included in the audience of some 250 people, were representatives of local government, associations, organizations concerned with the introduction of civil supersonic aircraft, and guests from some foreign governments.

In addition to the actual sonic booms, which were generated by Lightning aircraft, there were some simulated booms, generated by firing pairs of explosive charges, and some flyovers by a subsonic jet. The same program of events was staged twice, in the morning, when the audience experienced it outdoors, and in the afternoon, when the audience experienced it indoors.

Extensive monitoring of the actual and simulated booms was performed and some subjective studies involving a jury were conducted. Experts observed the effects of the booms on buildings and on livestock. The present report describes how the exercise was conducted from an operational point of view and what monitoring measurements were made.

S-29
SONIC BOOMS
Harvey H. Hubbard
Physics Today, Vol. 21, Feb. 1968, pp. 31-37

This paper presents a broad general review of sonic boom theory and the results of some of the sonic boom flight-test experiments that have been conducted. Topics discussed include: (1) generation; (2) prominent boom researchers; (3) energy spectra of N-waves; (4) lateral spread; (5) atmospheric effects; (6) human response; (7) structural response; and (8) damage reports.

S-30
REVIEW OF SONIC BOOM THEORY
Wallace D. Hayes
AFOSR-UTIAS Symposium on Aerodynamic Noise, Toronto May 20-21, 1968, pp. 387-396

This paper presents a review of standard sonic boom theory. Particular emphasis is placed on the propagation of sonic booms in a horizontally stratified atmosphere with horizontal winds. The theory is described as geometric acoustics plus a modification for nonlinear effects. Similitude laws are presented for the flow near a caustic, where the standard theory fails. For details of the modified theory of geometric acoustics and the similitude laws for caustics, the reader is referred to capsule summaries P-98 and P-91, respectively.

The portion of this paper dealing with propagation gives a very good mathematical description of the theory. A later review by Hayes (see capsule summary S-42) does not go into the mathematics of propagation theory in as much depth as the present paper, however it covers a much broader range of topics concerning sonic booms than does the present paper.

S-31
RECENT RESULTS OF SONIC BOOM RESEARCH
Harvey H. Hubbard
AFOSR-UTIAS Symposium on Aerodynamic Noise, Toronto May 20-21, 1968, pp. 397-408

A brief state of the art review of sonic boom technology is presented in this paper. Topics discussed include: (1) basic physical phenomena; (2) influence of the atmosphere; (3) effects on structures; and (4) effects on people.

S-32
A SURVEY OF SONIC BOOM THEORY
R. Seebass
NASA-CR-108838, June 19, 1968

This report is exactly the same as the one discussed in capsule summary S-39. The reader is referred to that capsule summary.

S-33
RESULTS OF RECENT NASA RESEARCH PERTINENT TO AIRCRAFT NOISE AND SONIC BOOM ALLEVIATION
Harvey H. Hubbard, Domenic J. Maglieri, and William H. Mayes
ICAS Paper No. 68-02, Presented at The Sixth Congress of the International Council of the Aeronautical Sciences, Deutches Museum, München Germany, Sept. 9-13, 1968

A brief review is presented in this paper of research conducted by NASA involving the alleviation of aircraft noise and sonic boom. The topics discussed concerning sonic boom include: (1) aircraft design considerations; (2) signature variability; (3) overpressure probability distributions; (4) aircraft operational factors; (5) sonic boom simulation; (6) structural response; (7) seismic response; and (8) human response.

S-34
SONIC BOOM RESEARCH (1958-1968)
Johnny M. Sands
Federal Aviation Administration Report, Nov. 1968

A brief chronology of sonic boom research is presented in this report. The report is divided into three parts. Part I presents a chronological listing of the various field research programs, identifies the government agencies involved, and provides a brief summary of the work accomplished. Part II describes some of the laboratory experiments and theoretical studies that have been conducted under government sponsorship. Part III contains a listing of publications resulting from these research programs.

S-35
STATE OF THE ART OF SONIC BOOM THEORY
Wallace D. Hayes
NASA SP-180, Second Conference on Sonic Boom Research, 1968, pp. 181-182

A very brief and general discussion of the state of the art of sonic boom theory as of 1968 is presented in this paper. The important points made are as follows:

1. Propagation of sonic booms from slender aircraft can be adequately calculated using linear theory and geometric acoustics together with a nonlinear modification of the signature.

2. The problem of predicting sonic boom signatures near a caustic remains unsolved.

3. Other problem areas in the theory include that of nonlinear effect on ray tubes, diffraction into shadow zones, and nonlinear effects near the aircraft.

4. More work is needed concerning the effects of atmospheric turbulence.

5. The one inescapable parameter controlling minimum sonic boom intensity is the lift of the aircraft plus a term which depends upon the increase of engine jet exit area over capture area.

Hayes presented a much more complete and extensive summary of the state of the art of sonic boom theory in a later paper (see capsule summary S-42).

S-36
AERODYNAMICS, NOISE, AND THE SONIC BOOM
W. R. Sears
AIAA Journal, Vol. 7, No. 4, April, 1969

In the brief portion of this paper dealing with sonic boom a review is presented of basic concepts in sonic boom generation and minimization theory. Topics discussed include: (1) Whitham's theory; (2) supersonic area rule; (3) signature "freezing" in a density-stratified atmosphere; and (4) sonic boom reduction by engine streamtube modification.

S-37
SURVEY OF UNITED STATES SONIC BOOM OVERFLIGHT EXPERIMENTATION
John O. Powers and Domenic J. Maglieri
AGARD Conference Proceedings No. 42, Aircraft Engine Noise and Sonic Boom, May 1969, pp. 15-1 thru 15-35

An extensive review of sonic boom flight experiments and sonic boom theory is presented in this paper. The following topics are included in the discussion: (1) chronological review of flight-test programs; (2) signature characteristics; (3) altitude effects; (4) lateral spread; (5) wavefront ground intersection; (6) atmospheric effects; (7) aircraft maneuvers; (8) statistical variability of peak overpressures; (9) structural effects; (10) human response; (11) seismic effects; (12) effects on other aircraft; (13) damage claims data; (14) St. Louis community response study; (15) Oklahoma City sonic boom program; (16) White Sands Missile Range sonic boom tests; (17) Edwards Air Force Base sonic boom experiments; (18) instrumentation techniques; (19) the Hayes-ARAP computer program; (20) signature aging; and (21) maneuver calculations.

It can be seen from the list of topics covered that this is a very broad review.

S-38
SONIC BOOM THEORY
R. Seebass
Journal of Aircraft, Vol. 6, No. 3, May-June, 1969, pp. 177-184.

This paper presents a summary of the state of the art of sonic boom theory as of 1969. A concise mathematical description of sonic boom generation theory and sonic boom propagation theory forms the first half of the paper. The last half of the paper discusses sonic boom minimization theory.

The following topics are covered in the discussion of sonic boom generation and propagation theory: (1) the contributions of aircraft volume and lift to the area distribution of the equivalent body of revolution; (2) the relationship between the cross-sectional area distribution of the equivalent body of revolution and the pressure disturbance due to the body; (3) the relationship between the F-function and the equivalent body area distribution; (4) the distortion of the waveshape due to cumulative nonlinear effects; (5) the introduction of shock waves to render the solution single-valued; (6) use of principle of constant energy flux along a ray tube to compute overpressure in an inhomogeneous atmosphere; (7) the "freezing" effect on the pressure signature shape due to the nearly exponential increase of density with decreasing altitude; (8) the effects on overpressure of aircraft altitude, weight, length, and volume; and (9) the relative contributions of lift and volume to the overpressure.

In the discussion of sonic boom minimization theory the following topics are included: (1) the use of engine streamtube area reduction to reduce sonic boom (see capsule summary M-34 for a discussion of this topic); (2) the design of aircraft having no shock waves in their pressure signature (see capsule summary M-3. for a discussion of this topic); and (3) minimum achievable shock pressure rise for a given aircraft length and flight conditions (see capsule summaries M-43, M-53, and M-61 for discussion of this topic).

This paper, along with the similar paper by Hayes (see capsule summary S-42) is one of the best concise summaries of sonic boom theory that has been written.

S-39
SST AND SONIC BOOM HANDBOOK
William A. Shurcliff
Ballantine Books, Inc.,
Feb. 1970

This paper contains information about SST's and the sonic boom. Most of this information was taken from various newspaper and magazine articles. The paper is highly biased against SST's and sonic booms and contains many unsubstantiated opinions.

S-40
REPORT ON THE SONIC BOOM PHENOMENON, THE RANGES OF SONIC BOOM VALUES LIKELY TO BE PRODUCED BY PLANNED SST's AND THE EFFECTS OF SONIC BOOMS ON HUMANS, PROPERTY, ANIMALS, AND TERRAIN
Attachment A of ICAO Document 8894, SBP/II, Report of the Second Meeting of the Sonic Boom Panel, Montreal, October 12 to 21, 1970

This report is composed of six chapters, each dealing with a certain aspect of sonic boom phenomena. The present capsule summary summarizes only the first chapter, which is entitled "General Description of the Sonic Boom Phenomenon."

The topics discussed in chapter 1 include: (1) propagation; (2) the sonic boom waveform; (3) the sonic boom carpet; (4) effects of atmospheric turbulence; (5) effects of the ground environment; and (6) calculation and measurement of individual sonic booms. The discussion of each of these topics is brief and general.

S-41
SONIC BOOM AND THE SUPERSONIC TRANSPORT
Richard M. Roberds
Air University Review, Vol. 22, July-August 1971, pp. 25-33

A very general discussion of sonic boom theory is presented in this paper. Topics discussed include: (1) generation; (2) atmospheric effects; (3) aircraft design; (4) human response; (5) property damage; and (6) overpressure variability.

S-42
SONIC BOOM
Wallace D. Hayes
In Annual Review of Fluid Mechanics, Vol. 3, M. Van Dyke, et al, eds., 1971. pp. 269-290

A summary of the state of the art of sonic boom theory as of 1971 is presented in this paper. The topics covered include: (1) flow near the aircraft; (2) propagation; (3) nonlinear distortion; (4) calculation of sonic boom signatures; (5) focusing and caustics; (6) effects of turbulence; and (7) optimization and reduction of sonic boom.

The discussion of the flow near the aircraft includes linearized supersonic aerodynamic theory, the equations for calculating the F-function, the equations for calculating the equivalent area distribution of the aircraft, and the relation between drag and sonic boom. The discussion of the propagation of sonic booms is concerned mainly with geometrical acoustics and Blokhintzev invariance (see capsule summary P-98). The section on nonlinear distortion explains the age variable and the formation of shocks. The section on the calculation of sonic boom signatures shows how the calculations described in the three preceding sections are combined, and it also discusses the "freezing" effect.

Included in the discussion of problems involved in calculating the pressure field in the vicinity of a caustic is the description of a transition maneuver for avoiding the superboom produced by an aircraft as it accelerates to supersonic speeds. The caustic beneath the aircraft is kept up off the ground at the beginning of the maneuver by a combination of forward acceleration and a mild pullover. The forward acceleration of the aircraft is reduced suddenly during the maneuver and the aircraft suddenly put into a mild pullup. As a result of this maneuver, the focal point is thrown suddenly from a position well above the ground to a position well below the ground. No superboom can be produced at ground level if the velocity of the focal point in the transition maneuver is made to be greater at ground level than the speed of sound.

The discussion of the effects of turbulence summarizes the various theories that attempt to explain the "spiking", "rounding" and long rise times of sonic boom pressure signatures.

Finally, the discussion of sonic boom minimization briefly explains the two possible approaches: (1) accepting the asymptotic N-wave profile and minimizing the shock strength with given aircraft gross weight; and (2) maximizing the aircraft gross weight under the conditions that the signature at the ground have no shock and have no greater than a given rate of pressure increase.

This paper, along with the similar paper by Seebass (see capsule summary S-38) is one of the best concise summaries of sonic boom theory that has been written.

S-43
COMMENTS ON SONIC BOOM RESEARCH
R. Seebass
NASA SP-255, Third Conference on Sonic Boom Research, 1971, pp. 411-412

A very brief discussion is presented in this paper on what the future direction and scope of sonic boom research should be. The significant points made are as follows:

1. The nature of the superboom must be determined and a method of predicting its strength must be derived.

2. Threshold Mach number flight should be investigated more thoroughly.

3. More emphasis should be placed on the sonic boom component of hypersonic transport research.

4. Sound theoretical ideas must continue to be tested in the wind tunnel.

5. Field tests should be limited to projects with high scientific content.

6. Sonic boom research must continue, but not at the expense of research that relates directly to the aircraft's performance.

A later report by Haglund and Kane (see capsule summaries P-162 and TM-13) presents the results of an investigation that was in line with the first two suggestions of the present paper.

S-44
SONIC BANG MEASUREMENTS DURING EXERCISE SUMMER SKY
D.R.B. Webb, F. L. Hunt, R. J. Pallant, & W. L. Walters
Ministry of Aviation Supply, Aeronautical Research Council, Reports and Memoranda R. & M. No. 3659, 1971

Exercise Summer Sky consisted of a series of supersonic flights made by Lightning aircraft over three areas in Southern England during July 1967. The purpose of these flights was to observe public reaction to sonic booms. Sonic boom pressure signatures were measured by the R.A.E. at selected points in each of the three areas. One of the selected points in each area was in the nominal focus area of the flight paths, and for this purpose a ship was used as a monitoring station because the flight paths were arranged so that the focus areas occurred at sea. In this report the recorded waveforms are shown and discussed, together with details of the aircraft tracks and relevant meteorological conditions. See capsule summary S-46 for a brief discussion of the public reaction to these flights.

S-45
SONIC BOOM GENERATION PROPAGATION AND MINIMIZATION
Antonio Ferri and Ira R. Schwartz
AIAA Paper No. 72-194, AIAA 10th Aerospace Sciences Meeting, San Diego, California, Jan. 17-19, 1972

An extensive review is presented in this paper of sonic boom theory and the supporting experimental research. The topics discussed include: (1) linear theory in local field of aircraft; (2) higher order approximations for use in predicting sonic boom signatures; (3) wind tunnel techniques and difficulties; (4) atmospheric effects; (5) ground reflection effects; and (6) sonic boom minimization techniques. The discussion of each of these topics is concise and qualitative in that the mathematical formulations of the various theories are not presented

S-46
RECENT SONIC-BANG STUDIES IN THE UNITED KINGDOM
C. H. E. Warren
The Journal of the Acoustical Society of America, Vol. 51, No. 2 (Part 3), February 1972, Sonic Boom Symposium, pp. 783-789

This paper summarizes the significant sonic boom studies made in the United Kingdom between 1965 and 1970. The field experiments, flight tests, and laboratory studies summarized include: (1) Exercise Summer Sky; (2) Exercise Gambit; (3) sonic boom trials on Concorde 001 at Istres; (4) Exercise Trafalgar; (5) Exercise Babel; (6) Exercise Underlord; (7) experiments on greenhouses; (8) studies at the National Physical Laboratory; and (9) studies at the Institute of Sound and Vibration Research.

Exercise Summer Sky was conducted in July 1967. It consisted of a series of supersonic flights made by Lightning aircraft over three areas in southern England. The average boom intensity generated by these flights over land areas was about 1 psf. The purpose of the flights was to observe public reaction to sonic booms. Eleven flights were made, resulting in about 50 million boom-person exposures. Approximately 12,000 complaints and 788 claims for damage resulted from the flights. Total damage payments amounted to $9800, $2600 of which was for glass damage, $3400 for damage to ceilings, and $1200 for damage to roofs and chimneys.

Exercise Gambit was conducted during the summer of 1969. It was designed to obtain some preliminary information on atmospheric distortion effects. Waveforms measured in a balloon flying on the track of the aircraft (type not mentioned in this paper) were compared with those measured on a ground array at the same time. Nine sonic booms were studied under varying meteorological conditions and some structural studies on a church in the area were also made. The results of this exercise are not discussed.

The Concorde 001 (French-assembled) made four overpasses at a Mach number of 1.3, two being at 45,000 feet and two at 37,000 feet at Centre d'Essais en Vol at Istres, France in December 1969. Pressure signatures were measured at approximately 40 measuring stations spread out along the flight track. It was found that the measured overpressures agreed very well with standard calculations. The calculations predicted, as was found from the measurements, that the waveform would not attain its asymptotic shape at the ground for a flight altitude of 37,000 feet. The calculated overpressures were usually within 10% of those measured and the calculated signature intervals were within 3% of those measured. For an illustration of the measured waveforms and a summary of the signature characteristics see capsule summary SBA-23.

All sonic boom studies made in connection with the flight trials of the Concorde 002 (British-assembled) were given the code name Exercise Trafalgar. These studies included structural response, human response, and animal response studies. However, no results of these studies

are given in this paper.

Exercise Babel was conducted · ing 1968. Simulated booms generated by losive line charges were used to test the uctural response of a specially built test house. No results of this test are given.

The vibrational response induced in 13 British cathedrals by various causes, including simulated sonic booms was investigated in Exercise Underlord. The methods of inducing vibration included bell ringing, organ playing, road traffic and a special explosive charge from which it was possible to calculate the vibrational response that would be induced by a sonic boom. It was found that the level of response predicted for vibrations induced in bell towers by sonic booms was of the same order of magnitude as that due to the existing environment. The level of vibration due to sonic booms (predicted) was an order of magnitude less than the existing environment for the cathedral walls and an order of magnitude greater than the existing environment for the roofs, vaulting, and windows.

Explosive line charges were used to test the effects of simulated sonic booms on greenhouses. The pressure signature produced by this simulant was very close to that of an actual sonic boom, especially in its low frequency energy content. The table below, which was taken from this paper, shows the results of these tests. It can be seen that most of the damage to the greenhouse windows (out of a total of 35,000) occurred following events 3 and 4, even though events 8 and 9 w of much higher intensity. It was thought tha the first few booms of the program triggered off most of the damage that was on the verge of occurring, and there were fewer subsequent damages because these had already failed.

Event No.	Characteristic overpressure N/m²	lbf/ft²	Number of additional damages to panes
1	86	1.8	8
2	48	1.0	11
3	96	2.0	80
4	62	1.3	79
5	81	1.7	20
6	86	1.8	11
7	96	2.0	7
8	148	3.1	15
9	200	4.2	8

History of damage to glass in greenhouses

The work of Johnson and Robinson on calculating the loudness of sonic booms (see capsule summary HRSC-50) is mentioned in conjunction with the discussion of work being conducted at the National Physical Laboratory. Brief mention is also made of various studies conducted at the Institute of Sound and Vibration Research concerning structural response and human response.

This paper is an update of an earlier paper by Warren (see capsule summary S-23) in which he summarized the flight-test studies conducted in the United Kingdom between 1960 and 1965.

S-47

SONIC BOOM EXPOSURE EFFECTS 1.2: THE SONIC BOOM-GENERATION AND PROPAGATION

C. H. E. Warren

Journal of Sound and Vibration, Vol. 20, No. 4, 1972, pp. 485-497

A fairly extensive discussion of sonic boom generation and propagation theory is presented in this paper. The first portion of the paper consists of a general discussion of the physical aspects of the generation and propagation of sonic booms, including focusing, ground reflection effects, and typical sonic boom characteristics. The second portion of the paper presents the mathematical formulation of sonic boom generation and propagation theory. Included in this formulation are: (1) the relationship between the F-function and the aircraft's distribution of cross-sectional area and lift; (2) the relationship between the overpressure and the F-function; (3) geometric acoustics; (4) waveform aging; (5) appearance of shocks; (6) waveform freezing; (7) effects of focusing; (8) waveform distortion by turbulence; (9) and an approximation appropriate to steady level flight in an isothermal atmosphere. All of these topics, except (6), (7), and (8) are discussed in some mathematical depth.

This is an excellent review of sonic boom generation and propagation theory. Similar earlier reviews were presented by Seebass and Hayes (see capsule summaries S-38 and S-42, respectively). However, minimization theory was also discussed in those two papers, but not in the present paper.

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